Lifetime and Reliability

Long life has been billed as a key advantage of LEDs, but understanding and communicating how LED products fail and how long they last can be challenging. While LED-based products hold the potential to achieve lifetimes that meet or exceed their traditional counterparts, manufacturer claims can be misconstrued by users who do not fully understand LED product failure mechanisms or the difference between lifetime and reliability.

Introduction

All lighting products fail at some point; that is, they reach the end of their useful life. Under normal use and conditions, product failure results from design flaws, manufacturing defects, or wear-out mechanisms. The familiar bathtub curve (Figure 1) shows how failure rate typically changes over the life of a product.

For conventional, lamp-based lighting systems (e.g., incandescent, fluorescent, and high-intensity discharge), failure most commonly results when a lamp "burns out"—otherwise referred to as catastrophic failure. In almost all cases, other system components (e.g., the ballast or luminaire housing) last longer than the lamp, and have lifetimes that are not dependent on the lamp. Further, lamp replacement is easy and relatively inexpensive. As a result, it has been sufficient to consider only the lifetime of the lamp itself. Typically, manufacturers assign a lifetime rating to a lamp based on the time at which 50% of a large sample is expected to have stopped working, using measurements and predictive models. Historically, the use of this median time, denoted B_{50}, to represent the useful life of a product has worked acceptably well for completing economic analyses and calculating associated design parameters.

Unlike conventional lighting systems, LED systems are not necessarily lamp based; commercially available LED products include fully integrated luminaires, integral-driver lamps (with conventional bases), lamps with external drivers, and modules (with newly developed interfaces to other components), among others. Regardless of product type, LED system performance is typically affected by interactions between system components; for example, LED package lifetime is highly dependent on thermal management, and LED lamp performance can be dependent on the luminaire in which it is installed. Establishing a rated lifetime for a complete LED system is further complicated by the cost and impracticality of traditional life testing, especially because the continued development and advancement of LED technology can render results obsolete before testing is finished. Consequently, the typical approach to characterizing lifetime is no longer viable for LED systems.

LED Product Failure

The failure of any LED system component—not just the array of LED packages, but also the electronics, thermal management, optics, wires, connectors, seals, or other weatherproofing, for example—can directly or indirectly lead to product failure. Further, while some LED products will fail in a familiar catastrophic way, others may exhibit parametric failure—meaning they stop producing an acceptable quantity or quality of light. A complete characterization of the useful life of an LED product must consider the possibility of catastrophic or parametric failure for each system component, operating together as a system. At this time, however, there is no standard or well-accepted method for performing such a characterization. Consequently, understanding the intricacies of failure, lifetime, and reliability is very important for evaluating LED products.

Concerns about lifetime and maintenance have been around for a long time. *Credit: Ford Motor Company*

Some of the issues surrounding the lifetime of LED products are not completely unique. For example, fluorescent lamps also require a ballast and other system components that can fail, and lamp lifetime is somewhat dependent on ballast type. However, lamp designs and construction have changed slowly, allowing for the development of robust models for predicting lamp life and mature, reliable ballasts. As a result, the traditional focus on lamp rated life has been sufficient for deploying and managing fluorescent systems. When source life regularly meets or exceeds the lifetime of other components in a lighting system, however, lifetime management becomes more complicated. This is the case for a vast majority of LED products, as well as some new extra-long-life fluorescent lamps.

Failure of LED Packages

There are many components in an LED lighting system that can fail, but to date LED packages have been the focal point. LED packages rarely fail catastrophically, necessitating consideration

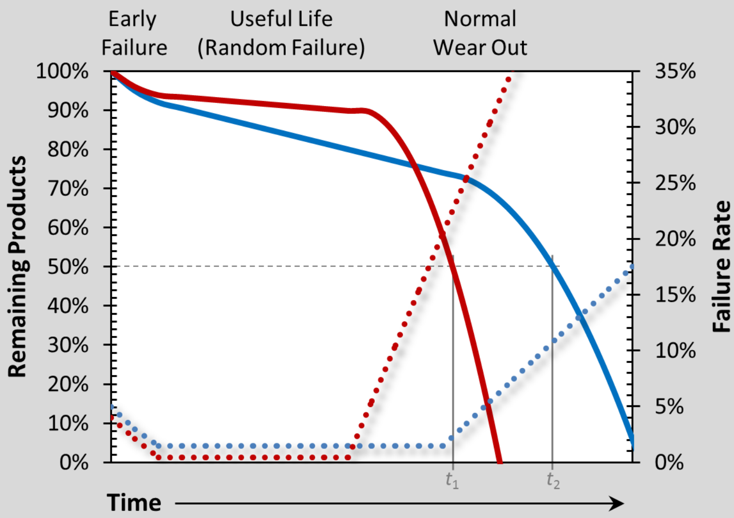

Figure 1. Failure rate (dotted lines) and percent remaining (solid lines) versus time for two hypothetical products. Reliability is the rate of random failure during the useful life phase, which is slightly lower (better) for the product shown in red. Using a 50% remaining metric for determining lifetime, the blue product has a longer rated life. Lifetime and reliability are not synonymous.

The plots of failure rate illustrate the bathtub curve, which typically arises from some combination of design flaws, material and manufacturing defects, and normal wear out. For LED products, design flaws may include insufficient thermal management, poor driver design, or incompatible materials, among others. Material and manufacturing defects are the primary contributors to early failure, otherwise known as infant mortality, as well as failure during the useful life period. Some manufacturers attempt to reduce or eliminate early failures by utilizing a "burn-in" period prior to shipment. Products that are well designed and well made should reach "normal" end of life, an event that can be caused by one or more failure mechanisms.

A desirable product has a short early failure period (with failures that can be identified during infant mortality testing), a long useful life with a low rate of random failure (i.e., is highly reliable), and a short wear out period (consistent with steeper slopes in the bathtub curve), allowing for more predictable end-of-life planning.

of parametric failures such as degradation or shifts in luminous flux, luminous intensity distribution, color temperature, color rendering, or efficacy. Of these, lumen depreciation has received the most attention, although there is little long-term data to confirm that it is the primary failure mechanism for LED products. Nonetheless, lumen maintenance is often used as a proxy for LED lamp or luminaire lifetime ratings, in large part due to the availability of standardized methods for measuring and projecting LED package lumen depreciation.

A lumen maintenance failure criterion is typically specified as a relative percentage of initial output, most often the point when output has dropped to 70% of the original value, denoted L_{70}. Because failures among a set of installed lamps or luminaires do not all occur simultaneously, lumen maintenance ratings are usually established based on the time at which 50% of a sample of products are expected to reach L_{70}, denoted L_{70}-B_{50}.

Other ways of conveying lumen maintenance performance have also been introduced. One notable method, offered as a reporting option for LED Lighting Facts,[1] is to identify the expected lumen maintenance at a fixed time interval (e.g., 25,000 hours). This may allow for more effective comparisons between products, especially when the calculated L_{70} value exceeds the intended product use cycle or the anticipated lifetime of another component in the system.

While lumen maintenance is important, other forms of parametric failure for LED packages must not be overlooked. For example, color shift may be more detrimental than lumen depreciation for some applications. It is, however, more difficult to predict, and is generally considered an aesthetic issue rather than a safety issue. For these reasons, it has received less attention than lumen depreciation. Substantial changes in luminous intensity distribution are also a potential cause of failure, but they are most often associated with changes in lumen output. For example, if half of the LEDs in a luminaire stop working, both the distribution and lumen output may be altered.

Failure of Other Components

Aside from the LED package itself, many other system components, like the driver, can cause an LED product to fail. Like any electronic device, a driver has a useful life that is related to the lifetime of its internal components, such as electrolytic capacitors, and that is strongly dependent on operating temperature. Ideally, the expected lifetime for the LED package(s) and the driver used in a product would be similar; however, given the long lifetimes of today's LED packages, the driver is the weak link for some currently available LED products, as illustrated in Figure 2. Market pressures to minimize cost or comply with specific form factors pose challenges for the longevity of LED drivers, particularly for lamp products.

Other components in an LED system may similarly struggle to outlive the LED packages. Thermal management components may become less efficient as they accumulate dirt and debris, and optical materials have been known to discolor or otherwise degrade over time, especially in high temperature environments. Gaskets and other materials may age prematurely due to compatibility issues with adjoining components. Oftentimes, the failure of auxiliary components is difficult to predict, and may only be exposed by real-world installations that have been operating for some time. Thankfully, as the body of knowledge surrounding the construction and materials of LED lighting systems has grown, it has become easier to recognize and avoid potential problems.

Standards

The measurement of lumen (and color) maintenance for LED packages is prescribed by IES LM-80-08 (*Measuring Lumen Maintenance of LED Light Sources*), while the projection of lumen maintenance beyond the duration of available LM-80 data is prescribed by IES TM-21-11 (*Projecting Long Term Lumen Maintenance of LED Light Sources*). TM-21 lumen maintenance projections can be applied to luminaires (and possibly lamps), through the proper use of in-situ temperature measurement; however, even if this extrapolation is done correctly, it can only be used to estimate the onset of one failure mode: lumen depreciation. Two new documents are slated to define standards for measuring the lumen and color maintenance of lamps and luminaires (IES LM-84), and projecting the lumen maintenance of lamps (IES TM-28); the lumen maintenance projection for luminaires is likely to be addressed in a future revision of TM-28 or a separate standard.

1 *http://www.lightingfacts.com/Downloads/Lumen_Maintenance_FAQ.pdf*

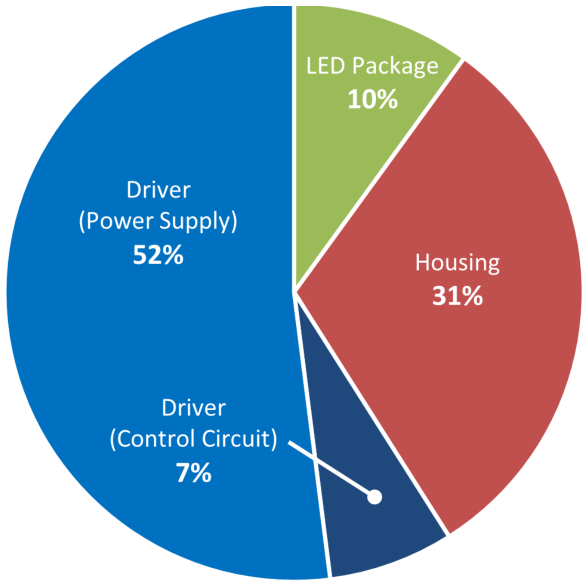

Figure 2. The distribution of failures over 34 million operating hours for one manufacturer's family of outdoor luminaires. A total of 29 fixtures failed out of more than 5,400 (0.56%). *Source: Appalachian Lighting Systems, Inc.*

Lifetime and Reliability

The rated lifetime assigned by a manufacturer is a statistical estimate of how long a product is expected to perform its intended functions under a specific set of environmental, electrical, and mechanical conditions. It is specifically related to normal wear out and end of life behavior. Typically, a single number is given as an estimate of a more complex distribution of failures; some products will fail before the rated lifetime, and some will fail afterwards. The rated lifetime of a product may be affected by its design, materials, component selection, manufacturing process, and use environment, among other factors. Importantly, the rated lifetime for a complete system cannot be longer than the in-situ lifetime for any of its components. The useful life of a product corresponds to the middle portion of the bathtub curve, where failures result from unexpected random events, and the failure rate is ideally constant.

Reliability is a different statistical measure of performance that, in principal, describes the ability of a product to perform its intended functions under a specific set of conditions and for a specific period of time. Reliability estimates are typically made for some portion of a product's useful life phase, prior to the point at which normal wear out starts to generate mass failures in a population of products. No matter how well engineered a product is, some samples will inevitably fail early; reliability is essentially a measure of the probability of these unanticipated failures, which are typically random. In relation to the bathtub curve, reliability estimates are made for the useful life (i.e., middle) portion of the curve, and are often reported as the mean time between failures (MTBF). Note that while both lifetime and MTBF are typically reported in hours or years, the latter is actually an average failure rate metric, rendering direct comparison between the two ratings meaningless and cause for misguided conclusions. For example, while a lifetime of 100,000 hours might be considered excellent, a ballast or driver MTBF of 100,000 hours means that over a 10-year (continuous) useful life period, 87.6% of the units will likely fail and need to be replaced.[2] Reliability metrics are useful for approximating the average maintenance interval of serviceable systems, but since MTBF only describes an average failure rate, the accuracy of such estimates is reduced for systems that do not have a constant failure rate during their useful life.

Serviceability

A serviceable product has components that are replaceable or repairable by regular maintenance personnel. Whereas lamp-based luminaires are almost all easily serviced in the field, some LED luminaires are not serviceable at all, or must be returned to the manufacturer for repair. Even for serviceable LED luminaires, the lack of standardized components—a situation that is improving—leads to several questions that must be answered on a product-by-product basis. For example, what components are replaceable and what are their rated lifetimes and reliabilities? Will replacement components be available in the future? Will next-generation components be backwards compatible?

Serviceability should factor into any purchasing decision where long or unproven system lifetime is expected, or where component lifetimes are not well known or well matched. While making a product serviceable typically adds some cost, concerns about the reliability of specific components over very long lifetimes can be alleviated if the components are replaceable or repairable. For some applications, a serviceable product with short-lived or less reliable components may be less costly to operate over its useful life than a more expensive product with well-matched component lifetimes.

Important Terms

Failure – The end of useful life; may occur either catastrophically (i.e., "burn out") or parametrically, where a product does not perform as intended (e.g., emits less than 70% of the initial output).

Lifetime – A statistical measure (or estimate) of how long a product is expected to perform its intended functions under a specific set of environmental, electrical and mechanical conditions. Lifetime specifications can only describe the behavior of a population; any single product may fail before or after the rated lifetime.

Mean Time Between Failures (MTBF) – The average time between failures during useful life for repairable or redundant systems.

Mean Time To Failure (MTTF) – The average time to failure during useful life for components or non-repairable systems.

Reliability – A statistical measure (or estimate) of the ability of a product to perform its intended functions under a specific set of environmental, electrical, and mechanical conditions, for a specific period of time. Reliability estimates for the entire useful life phase of a product are commonly reported using MTBF or MTTF.

Serviceability – The ability of a product to be repaired by regular maintenance personnel, typically through replacement of a subsystem or one or more associated components.

[2] *Percent failures is equal to the period of use divided by the MTBF. In this case, 87,600 hours/100,000 hours × 100% = 87.6%.*

Discussion

The accurate portrayal of LED product lifetime and reliability is important for consumers, manufacturers, and the lighting industry as a whole. It was not long ago that the default lifetime claim for an LED product was 100,000 hours, often with little or no supporting evidence. Such unsubstantiated claims can lead to significant user frustration that hinders the adoption of LED technology. Similarly, portraying the lumen maintenance of LED packages as the lifetime of a complete LED lamp or luminaire may misrepresent the actual performance of some products.

While standards groups are making steady progress characterizing the lumen maintenance of LED lamps and luminaires, more work is needed to project lifetime considering all possible failure modes. Testing a statistically significant sample of complete luminaires while addressing all possible permutations of features is an arduous task, but an approach that uses statistical methods for combining test results from multiple components can significantly reduce the testing burden; Figure 3 shows an example of such an approach, with the cumulative probability of failure plotted for a theoretical product, considering only the LED packages and driver. Accelerated (overstress) testing methods may also help reduce required testing time and improve reliability through the identification of design flaws and manufacturing defects. Continued work to standardize testing procedures, projection methods, and reporting practices is necessary and ongoing.

Consumers and specifiers can find a wide range of lifetime ratings for LED products, from less than 10,000 hours to more than 100,000 hours, depending on the type and quality of the product. However, these ratings are usually based exclusively on the expected lumen depreciation of the LED package, and little other data is readily available. Therefore, it may be difficult for consumers and specifiers to identify a truly long-life, reliable LED product. Even if consistent reporting of system-level lifetime and reliability data becomes commonplace, LED product variability may necessitate weighing various tradeoffs and asking additional questions. A well-designed product may take many forms, some of which may be more or less acceptable to a given user:

- Failure results from a single, well known, and easily understood wear-out mechanism.
- Failure results from multiple sources or mechanisms, but the product is designed such that the lifetime of each component is similar. For example, the lifetime of the LED driver matches the lifetime of the LED package(s).
- Failure results from multiple sources or mechanisms, but components with a shorter lifetime or lower reliability are easily serviced or replaced, thereby enabling an acceptable maintained system lifetime (and cost).

Users are advised to give thought to what balance between lifetime, reliability, serviceability, warranty, sustainability, and cost is necessary or ideal for their lighting application. Typically, the design and manufacture of products that last longer comes at a cost, yet the advantages of longer life may not be realized if the expected use cycle is less than the lifetime. For example, a building scheduled to be renovated in the next 10 to 15 years may not benefit from lighting products with a 30-year lifetime. Instead, it may be better to use a less expensive product with a shorter useful life, but higher reliability. On the other hand, shorter-lived products generate more waste and compromise sustainability goals or requirements. Minimizing the net amount of disposed material ideally results in the lowest user cost and environmental impact.

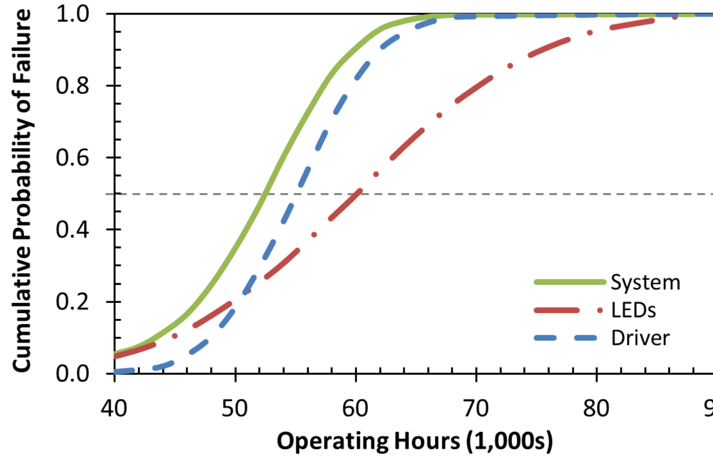

Figure 3. In this theoretical example, the rated life of the LED system is a function of both the LEDs and the driver. The rated life of the combined system is approximately 52,000 hours, which is less than for either component individually.

Lumen maintenance projections can help sophisticated users compare products, as long as their limitations are properly understood. Evaluating lifetime projections for other system components should also be considered, since the lifetime of a lamp or luminaire cannot be longer than the lifetime of any of its components. If payback period is critical, it may also be advisable to give extra consideration to the terms and credibility of the manufacturer's warranty.

Conclusion

As LED technology matures, some of the current issues surrounding the measurement and reporting of lifetime and reliability may abate. However, it is likely that products will continue to fail both catastrophically and parametrically, through various mechanisms. The dependence of LED package performance on other components will continue to require that discussions about lifetime be focused at the luminaire, and not component or even lamp level, as lamp performance in different luminaires can vary. Innovative luminaire designs and control strategies—such as variable drive products that maintain lumen output—will further complicate the measurement and reporting of lifetime. As with many performance attributes, LEDs have the potential to best other technologies in terms of longevity, but choosing the right product requires some understanding of expected failure mechanisms, lifetime, reliability, and serviceability, as well as asking the right application-specific questions.

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