LUMILEDS

WHITE PAPER

Evaluating the Lifetime Behavior of LED Systems

The path to a sustainable luminaire business model

One of the strongest propositions of power Light Emitting Diodes (LEDs) is their long lumen maintenance—their ability to continue producing light output for many years of use, in contrast to most conventional light sources, which force users to go through repeated and frequent failure-and-replacement cycles. The market perception of an LED's reliability is reinforced by the widespread practice among lighting manufacturers of offering long warranties on their LED luminaires.

Product testing regimes specified by industry standards make it possible for LED manufacturers to analyze lumen maintenance of a single LED, with great confidence, under virtually any operating condition. The most notable of these is IES LM-80 (LM-80), which is an "approved method for measuring lumen depreciation of solid-state (LED) light sources, arrays and modules," according to the U.S. Department of Energy (U.S. DOE). The U.S. DOE goes on to state that LM-80 "Does not cover measurement of luminaires" and that it "Does not provide methods for estimation of life." However, luminaire manufacturers have not had access to any additional information about LED behavior that would allow them to better understand and predict the "lifetime" behavior of the LEDs in their solutions. As a result, for some, lumen maintenance data has become a proxy for luminaire lifetime, which was clearly not the intent of LM-80 and is not an accurate assessment of luminaire lifetime.

Using lumen maintenance data that describes how a single LED behaves can create unplanned business risks and potentially affect end-customer experiences with LED solutions. What is now known and understood is that an array of LEDs behaves differently than a single LED. Additionally, it is possible to account for the extremely slim chance that a quality power LED will fail completely. Luminaire manufacturers are also learning how to better account for the lifetime behavior of the many other components that are used including drivers, optics, mechanical fixings and housings. Each of these is also a factor in determining the lifetime of a luminaire (see Figure 1).

Fortunately, responsible LED luminaire manufacturers are beginning to incorporate more detailed analysis and utilize the methods and tools that are covered in this paper so that they can more accurately project and report lifetime behavior.

For Consideration

To specify an LED array for 50,000 hours of operation while another system component is rated for just 25,000 hours raises engineering and manufacturing costs and does not maximize commercial opportunity.

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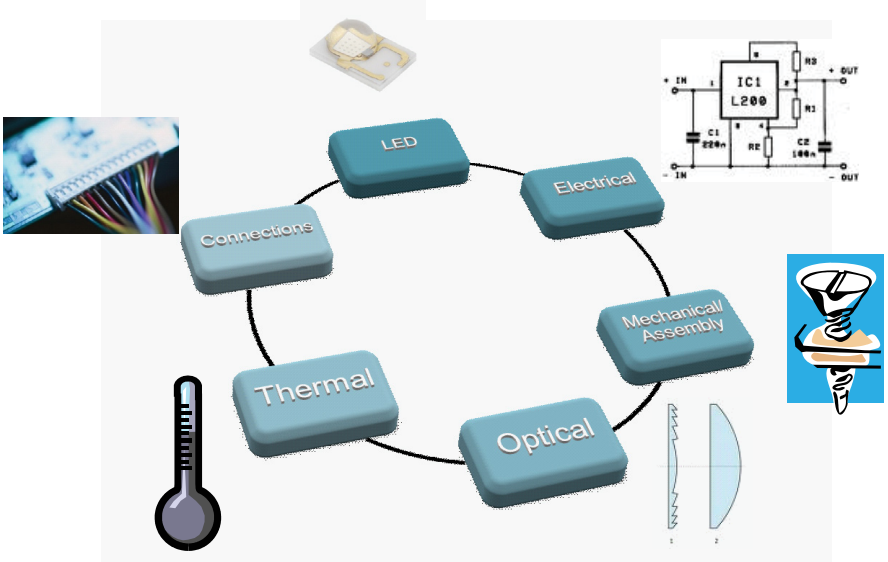

$$R_{SYSTEM} = R_{ELECTRICAL} * R_{CONNECTIONS} * R_{LEDS} * R_{OPTICAL} * R_{THERMAL} * R_{MECHANICAL}$$

Figure 1. LED system reliability.

Failure to truly understand the factors that determine reliability and use them to set an appropriate warranty period can result in either a higher than expected rate of claim against the warranty, or cause a product to be over-specified, potentially increasing the manufacturer's bill of materials unnecessarily.

The wider risk to the lighting industry is that, if reliability data are not properly understood and used, end user satisfaction with LED luminaires could be affected as their performance over time fails to meet the marketing claims. This in turn could affect demand for this highly efficient lighting technology, and slow the adoption of a class of products that will deliver enormous environmental benefit through reduced power consumption.

As an LED manufacturer, Lumileds cannot address the reliability of all the components in an LED system—no LED manufacturer can. LUXEON power LED reliability is, however, well understood and with this information, Lumileds has introduced a new concept for expressing the performance over time of power LEDs. Data sets, backed by product tests of long duration and already in the public domain, provide forecasts of lumen maintenance behavior, and separately of the catastrophic failure rates of our LEDs.

Lumileds is the first to combine this information about lumen maintenance and catastrophic failure rates in a robust predictive model that shows the probability of any given string of LEDs falling below any given threshold for light output. With this information, luminaire manufacturers can design for reliability and align market promises with solution performance.

Designing for reliability also helps luminaire manufacturers to offer warranties that are backed by valid forecasts of operating lifetime—provided these forecasts also take account of the probability of failure of the other components in the luminaire, and not just the LEDs.

To successfully proceed, there are important concepts that must be understood by users if they are to use LED manufacturers' reliability data as the basis for their luminaire warranties.

Luminaire manufacturers should also understand the methods and practices adopted by their LED supplier for testing and modeling the performance over time of their products. LED manufacturers should be able to show how robust are the raw data on which their predictive models are based—and industry-standard specifications represent the minimum with which testing regimes should comply.

They should also be clear about the predictive models they use to extrapolate lumen maintenance performance at any combination of drive current and temperature from their test cells.

Finally, they should show how the lumen maintenance and catastrophic failure predictive models for a single LED can be applied to arrays of LEDs, so that manufacturers can know the probability of lumen maintenance failure of any given array.

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The 'failure' modes of power LEDs, and their impacts on luminaire reliability

The concept of 'lumen maintenance' is well understood in the LED lighting industry: the light output from power LEDs is highest when new, and declines gradually over time. A common specification for power LEDs is for 70% lumen maintenance (that is, output at 70% of its peak) after 50,000 hours of operation.

All reputable power LED manufacturers conduct long-term performance testing of each variant of their products, and publish lumen maintenance data separately for each of these variants. A study of different lumen maintenance data sets from different manufacturers will reveal differences in their products' performance. This is not surprising as there are stark differences between LEDs in terms of:

- the precise chemical make-up of the semiconductor and optical system [encapsulant and primary lens]
- structure of the LED die
- the chemical makeup and implementation of phosphor conversion
- the mechanical structure of the device
- the materials used and device's thermal performance
- the materials used and consistency and quality of the LED manufacturing process

In combination, these factors result in significant differences in LED performance both when new and over time. Power LEDs are not generic devices and will vary in all performance aspects from manufacturer to manufacturer. Indeed, lumen maintenance is a competitive battleground for LED manufacturers, as customers demand LEDs that sustain lumen output over longer periods, and under more stressful conditions (that is, higher temperature and higher drive current).

An LED can be said to have 'failed' when its light output falls below a threshold expressed as a percentage of peak output. In this lumen maintenance 'failure' mode, of course, an LED is still producing light, but not at the specified level.

But lumen maintenance is not the only failure mode of power LEDs: they can also fail catastrophically, just like a conventional light bulb, and just like every other electronic or semiconductor product. In the case of a product such as the LUXEON Rebel from Lumileds, the rate of this so-called 'catastrophic failure' is extremely low, so low that the myth that LEDs never fail is still widely believed. Nonetheless, should a catastrophic failure occur, it could be of material significance depending on system design and the nature of the application.

In fact, there are a number of reasons why luminaire manufacturers should take account of catastrophic LED failure rates when designing a fixture. Perhaps the most obvious is that a catastrophic LED failure might leave a dark spot in an array. This could lead the user to the conclusion that the fixture is malfunctioning, even if a photometric examination showed that light output is still at or above its specified level.

Second, the concept of lumen maintenance has already been rehearsed above; any catastrophic failure, which eliminates the light output of an LED, will add to the decline over time in a lighting system's output.

Third, and less obviously, a catastrophic failure in an individual LED can cause instant failure in a complete luminaire or section of a luminaire. In part, this depends on whether an LED fails electrically 'open' or fails electrically 'short'. If it fails open, the power supply is cut off from every LED in the failed LED's string (in other words, to every other LED connected in series with the failed device), and the whole string goes dark. When an LED fails 'short', on the other hand, current continues to flow through the string allowing the luminaire to continue functioning.

LEDs like InGaN LUXEON Rebel LEDs can only fail short as there are no bond wires. When a device fails short, metal ions can still pass directly from anode to cathode, maintaining the integrity of the LED string's electrical circuit. It should be noted at this point that the catastrophic failure rate of LUXEON Rebel LEDs is extremely low.

A common "open" failure is due to a broken wire bond. Wire bonds are a feature commonly found in other power LEDs which therefore have two possible failure modes, "open" and "short."

Luminaire designers should also be aware of the risks inherent in connecting LEDs in parallel with each other, or in parallel strings, rather than in series. In a parallel topology, an electrical short of a single LED will cause the forward current to increase

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through some or all of the good LEDs. This increased forward current places additional electrical and thermal stress on the remaining LEDs. This in turn will cause them to fail faster than would have been predicted under normal operating conditions.

Additional failures cause the forward current to increase further and further, producing a cascade effect that leads to an accelerating series of failures.

For Consideration

Minimizing the number of failure modes that must be accounted for in the engineering process can save time, reduce costs and simplify the design for reliability process.

A luminaire should always be designed in accordance with good electrical practice for LED systems, that is:

- Use a current source to drive the LEDs
- Avoid the implementation of parallel connections between LEDs or between LED strings. All LEDs should be connected in series or in smaller strings of series connected LEDs, each with its own current source.

Provided these design for reliability practices are followed, the remaining LEDs in a string will continue to emit light as specified, even after one or more LEDs in the string have failed short.

Long-term LED performance testing: the foundation of reliability data

The long-term performance of LEDs, then, is affected by the rate of lumen maintenance and by the incidence of catastrophic failures; in combination, these two effects lead to a reduction in light output over time across a population of LEDs.

So the industry's critical need is for a trusted process that allows for more accurate predictions of system performance and for higher confidence in the engineering and business decisions associated with a luminaire.

But the user's confidence in such a model, and in the data that lie behind it, is a factor of the thoroughness of product testing carried out by the LED manufacturer. Therefore we start with a description of:

- how Lumileds reliability models are derived from its tests
- what the raw test results tell users about LED behavior
- how lighting system designers can use this knowledge

How reliability models are derived

Each luminaire designer needs to know the predicted long-term performance of their chosen LED under the specific conditions existing in their design. There is an infinite number of such conditions, so LED manufacturers cannot test for all possible conditions.

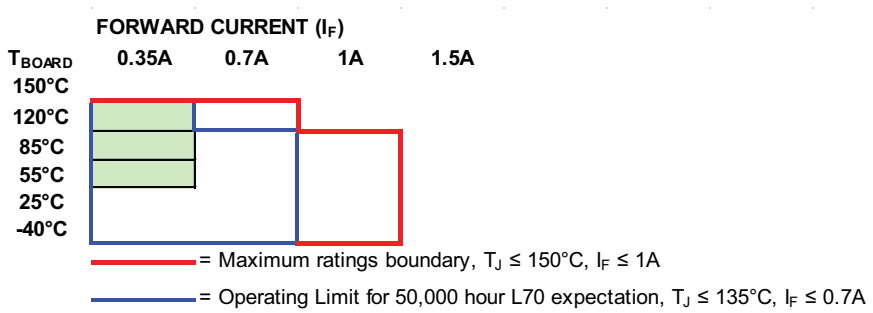

Figure 2. Cells needed for LM-80-08 specification.

All LED reliability models are therefore the result of extrapolation from a base set of data. The extrapolation occurs in two dimensions: operating conditions (drive current, and board/junction temperature); and time.

Lumileds datasheets show 'maximum' ratings for its LUXEON Rebel LEDs; users should not operate the LEDs beyond these limits. In Figure 2, the vertical scale refers to the temperature of the reliability stress board, which is approximately the same as the thermal pad temperature, T_S, and air temperature, T_A, surrounding the individual LEDs. Lumileds drives the individual LEDs on the reliability stress board with current sources. The horizontal scale refers to the forward current of the individual LEDs. Note that the heavy red line shows the boundary for the maximum ratings for the LUXEON Rebel ($T_J \leq 150C$, $I_F \leq 1A$). Lumileds also provides 'recommended' levels below these maximum ratings—up to this 'recommended' threshold; LUXEON Rebel LEDs offer typical lumen maintenance of at least 50,000 hours. Note that the lightweight blue line shows the boundary for recommended operation for the LUXEON Rebel ($T_J \leq 135C$, $I_F \leq 0.7A$).

Lumen maintenance model

To enable accurate extrapolation of lumen maintenance for any operating conditions, Lumileds tests at certain specific conditions. Three of these conditions are specified by the LM-80-08 standard for LED product testing, as defined by independent industry body IESNA (see Figure 2). Lumileds LM-80-08 reports (as of March 2010) are based on data from these three cells and from three additional cells, in order to make the extrapolation model even more robust (see Figure 3). Note that cell "Y" is a higher operating condition than the recommended operating conditions.

To support Lumileds lumen maintenance model's accuracy, further highly stressed cells can be added to the test set (see Figure 4). Note that cells "Y" are higher operating conditions than the recommended operating conditions. Note that cell "X" is a higher operating condition than the maximum ratings.

The lumen maintenance of an LED must also extrapolate into the future. Again, LM-80-08 specifies a minimum of 6,000 hours of testing. The ENERGY STAR® Manufacturer's Guide (September 2009) requires a minimum of 25 samples. Lumileds bases its lumen maintenance model on data from tests considerably longer in duration, and from a much larger sample size, than those specified by LM-80-08 and ENERGY STAR. In addition, Lumileds extrapolates lumen maintenance behavior using the same 'exponential extrapolation' model, as used by ENERGY STAR to predict the 6,000 hour limit points. By contrast, some LED suppliers use proprietary models that flatter the performance of their devices. The long-term lumen maintenance of a LUXEON Rebel can then be plotted on a graph. Figure 5 shows an example of a lumen maintenance graph produced in accordance with LM-80-08.

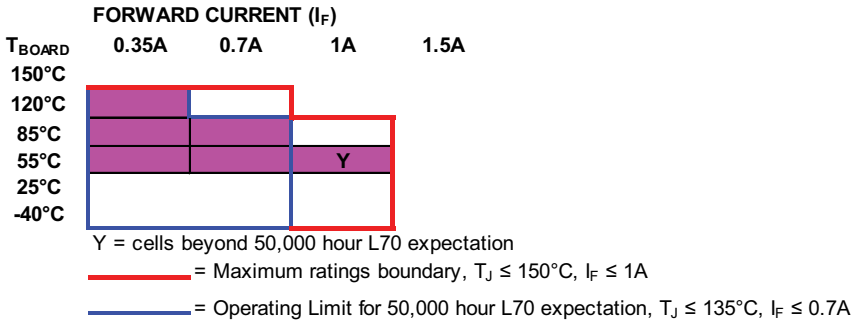

Figure 3. Cells used in Lumileds LM-80 Test Report.

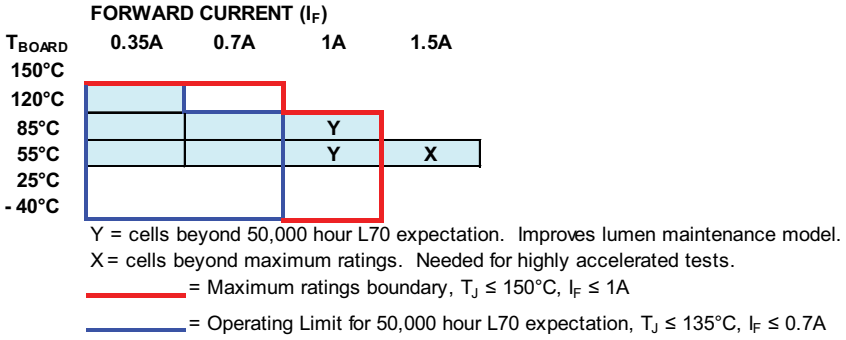

Figure 4. Cells used in Lumileds lumen maintenance model example.

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Lumileds testing regime goes far beyond the requirements of industry standards in an effort to give users of LUXEON Rebel products the most robust and accurate forecasts of their lumen maintenance performance available in the industry.

As stated in the introduction, it is common-but inappropriate-practice for luminaire manufacturers to use LM-80-08 lumen maintenance ratings to define the operating lifetime of a complete luminaire.

But an extrapolation of the rating only produces the average (median) lumen maintenance of a single LED under stated operating conditions—in Figure 5, the red curve shows median performance for a LUXEON Rebel LED at 85°C, 0.35A. This median performance of a single LED ignores a spread of results from best to worst across a population of LEDs. A lumen maintenance rating based on the median result for a single LED overstates the lumen maintenance performance of 50% of LEDs, and understates the performance of the rest.

For Consideration

What we see in the data from thousands of hours of testing is the degree that temperature, current, and time affects lumen maintenance. We know for Cool White LUXEON Rebel that drive current has a strong relationship to lumen maintenance and ambient temperature has a very low correlation to lumen maintenance. These relationships vary from product family to product family and from manufacturer to manufacturer. Some manufacturers report a strong correlation between ambient temperature and lumen maintenance, which should be clearly seen in their data. Extensive reliability testing has shown that air temperature has minimal impact on the lumen maintenance of the InGaN LUXEON Rebel family.

The industry-standard LM-80-08 lumen maintenance reports in use today therefore do not provide all of the necessary information that luminaire manufacturers need in order to predict the lumen maintenance behavior of a population of LEDs.

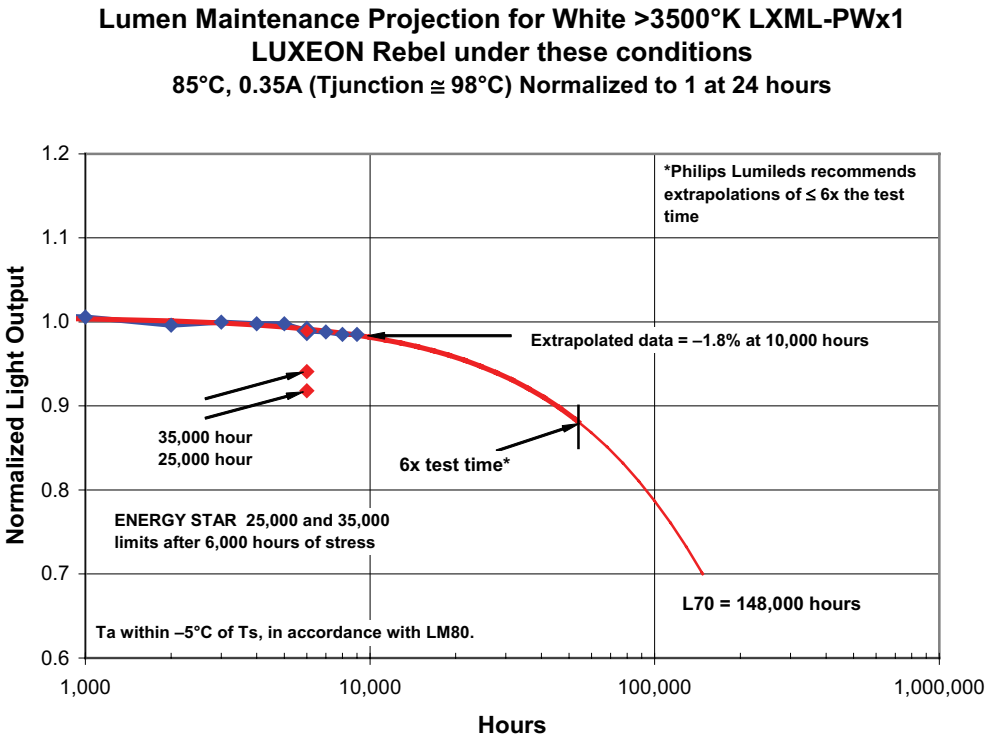

Figure 5. Long-term lumen maintenance data and L70 extrapolation.

While LM-80-08 does not require information about the spread in lumen maintenance behavior across a population of LEDs, Lumileds can derive this information from the tests described above. And this information can be expressed as a probability that a single LUXEON Rebel LED's lumen maintenance will cross a given threshold after a given operating time at a given set of operating conditions. An example of such a probability curve is shown in Figure 6.

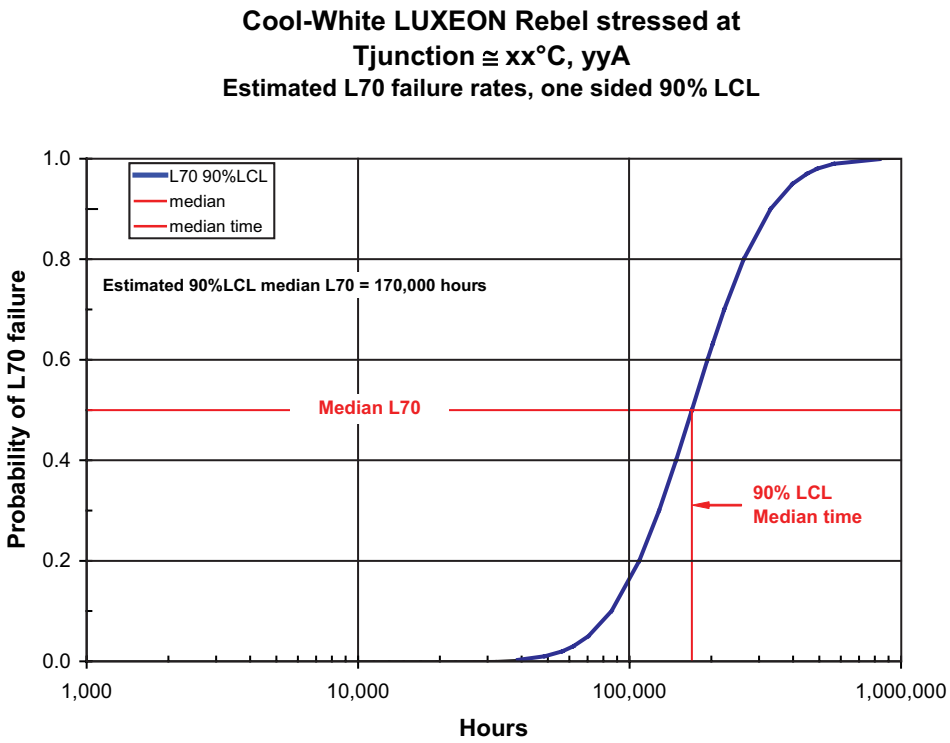

Figure 6. Lumen maintenance distribution from lumen maintenance model.

Now the luminaire manufacturer knows not just what the median lumen maintenance performance of a white LUXEON Rebel will be, but what the lumen maintenance of, for instance, the lowest 10% of white LUXEON Rebel LEDs will be.

Industry-standard reliability software then plots the trend lines between the actual results observed under the specific test conditions, enabling the prediction of lumen maintenance for any combination of drive current and temperature.

Catastrophic Failure Model

LED reliability, though, is not just a question of lumen maintenance. And while industry practice, as exemplified by the LM-80-08 standard, has focused on the production of lumen maintenance ratings for power LEDs, no such standard procedure exists for testing for catastrophic failure.

Lumileds has therefore created a testing procedure that can be employed by any LED manufacturer and which Lumileds is currently using for LUXEON Rebel LEDs. This uses the cells in the lumen maintenance-testing regime (see Figure 4 above), and adds more highly stressed conditions. (These conditions include exceeding the device's maximum 150°C temperature and maximum 1A current ratings.) The result is to force catastrophic failures at an accelerated rate in order to build a robust predictive catastrophic failure model (see Figure 7).

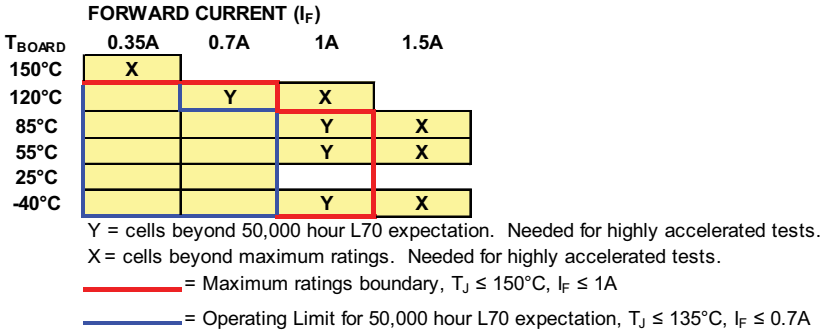

Figure 7. Cells used in Lumileds catastrophic failure model example.

This test set includes cells operating beyond the 'recommended' level and beyond the 'maximum' level. The data from these highly stressed conditions help to provide a greater degree of confidence in the extrapolations of the LEDs' performance at normal operating levels. Note that cells "Y" are higher operating conditions than the recommended operating conditions. Note that cells "X" are higher operating conditions than the maximum ratings.

As with the lumen maintenance model, the observed catastrophic failures in the test cells are fed into a standard reliability software package in order to develop a catastrophic failure rate model for a single LED with temperature and drive-current acceleration factors

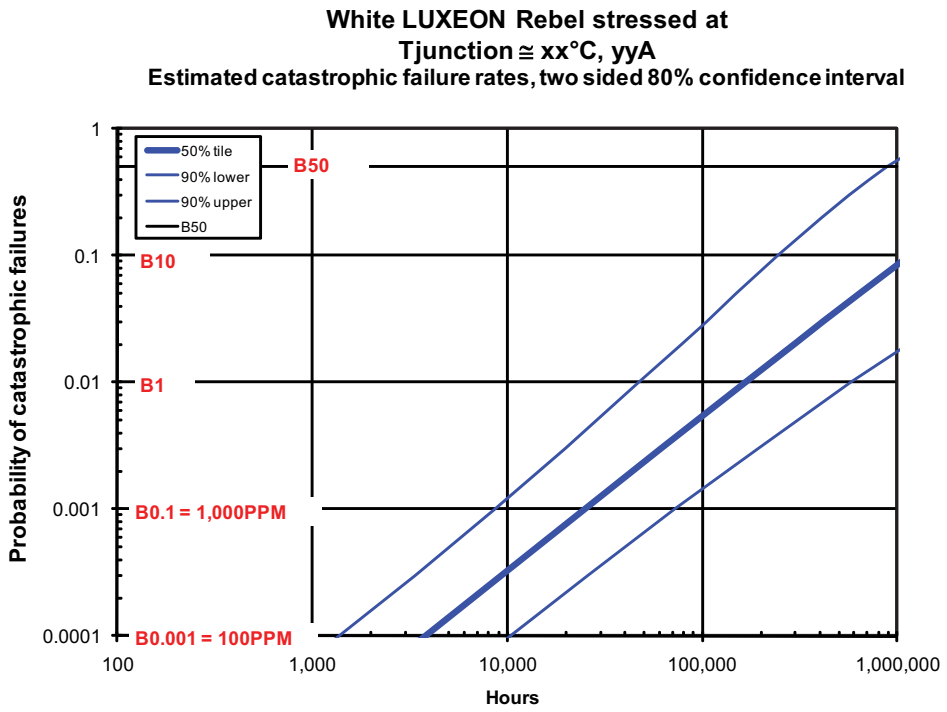

Figure 8. Catastrophic failure distribution from catastrophic failure model.

Now that we have a catastrophic failure model, we can estimate the probability that a single LED will fail at any given stress condition. This estimate can be expressed by means of a graph such as the one shown in Figure 8. Just as with lumen maintenance, the median figure (B50) for only catastrophic failure is not the most useful piece of information for luminaire manufacturers.

Note that there are three blue lines. The heavy blue line shows the estimated catastrophic failure rates based on the actual tests.

The catastrophic failure model also estimates the confidence interval. If this experiment was repeated, the failure rate model will vary slightly. Lumileds believes that if this experiment were done 10 times, then in 8 of 10 times, that the results would fall within the band shown in Figure 8. The line on the left represents the statistical estimate under which nine in every 10 times, the predicted time to failure would be better. This line is called the 90% Lower Confidence Level (or worst case). The line on the right represents the statistical estimate where one in 10 times, the predicted time to failure would be better. This line represents the 90% Upper Confidence Level (or best case).

Lumileds recommends the use of the more conservative 90% lower confidence line.

What the models tell manufacturers about LED behavior over time

Figure 9 shows examples of the lumen maintenance behavior of cool-white LUXEON Rebel LEDs, as predicted by the lumen maintenance model, when subject to different drive currents. Figure 10 shows examples of the lumen maintenance behavior of the LEDs when subject to different temperatures.

It is clear from this example for Cool-White LUXEON Rebel that additional temperature stress does very little to impair lumen maintenance. However, in this example for Cool-White LUXEON Rebel that increases in drive current cause much more marked declines in lumen output over time

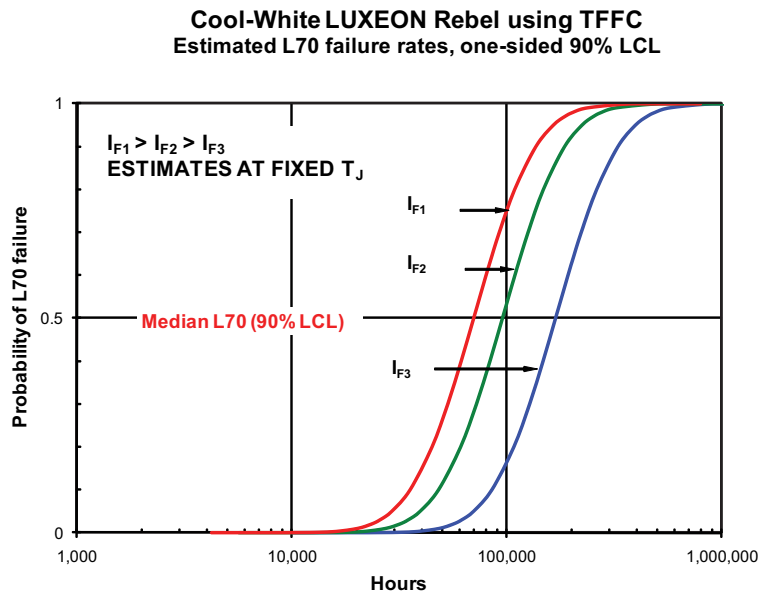

Figure 9. Impact of varying forward current in lumen maintenance model.

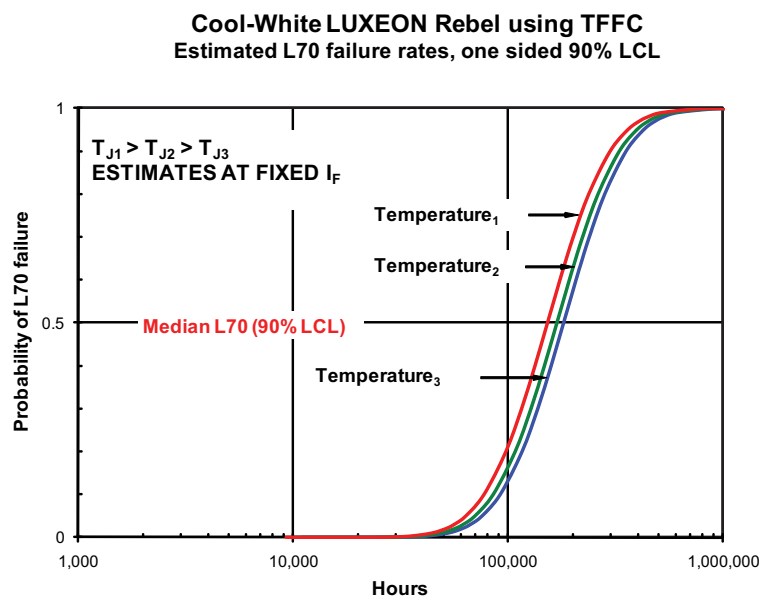

Figure 10. Impact of varying junction temperature in lumen maintenance model.

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As shown by this example, drive current has a large impact on lumen maintenance and temperature has only a small impact on lumen maintenance. However, it is important to talk to your LED manufacturer, as it may be different for other product families and LEDs from other manufacturers. Extensive reliability testing has shown that air temperature has minimal impact on the lumen maintenance of the InGaN LUXEON Rebel family.

Figure 11 shows examples of the catastrophic failure behavior of cool-white LUXEON Rebel LEDs as predicted by the catastrophic failure model, when subject to three different forward currents. All three lines represent the worst-case 90% lower confidence limits. The curve moves to the left, showing a higher rate of catastrophic failure, at higher drive currents.

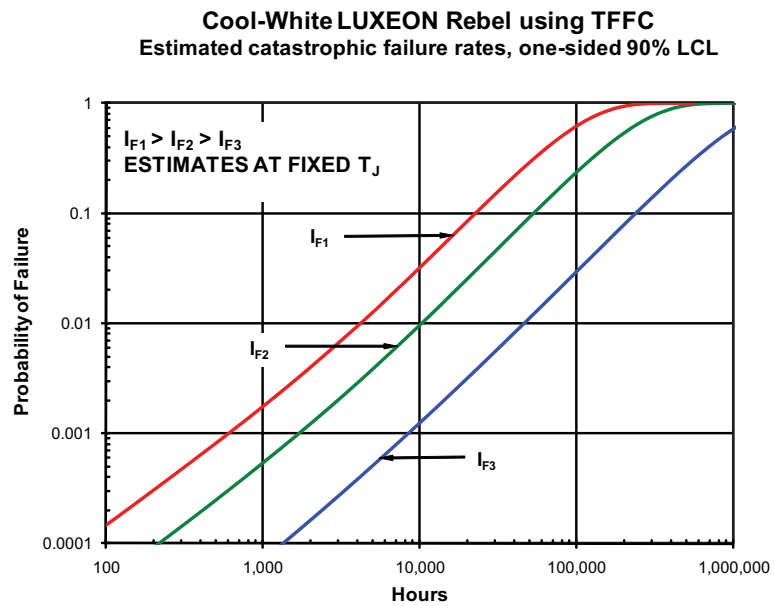

Figure 11. Impact of varying forward current in catastrophic failure model.

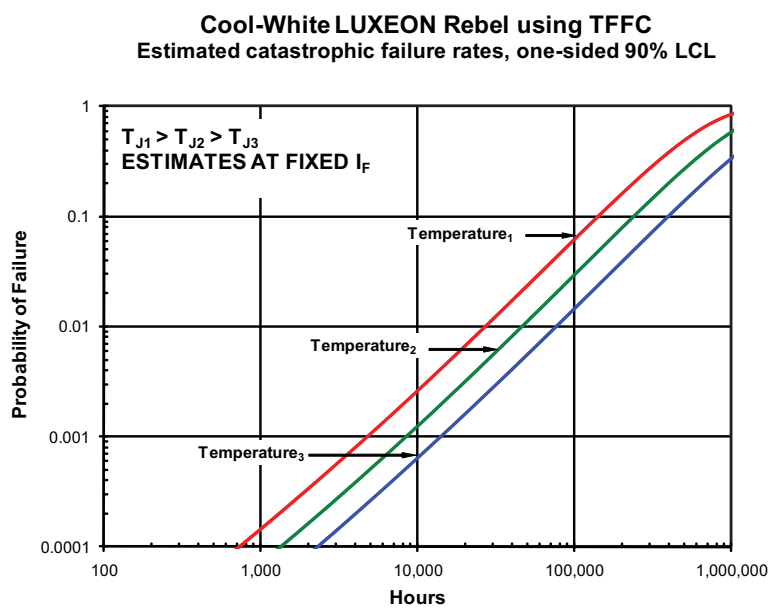

Figure 12. Impact of varying junction temperature in catastrophic failure model.

Figure 12 by contrast shows examples of catastrophic failure behavior of cool-white LUXEON Rebel under different temperature conditions. The curves move to the left, showing that temperature also affects the catastrophic failure rate.

In fact, reducing the junction temperature by 10°C extends the estimated time to failure by a factor of >1.2. Thus, good thermal management reduces catastrophic failure rates. Lowering the drive current also helps to reduce catastrophic failure rates.

This knowledge can be applied by luminaire manufacturers to tune their designs to their customers' requirements. Manufacturers can choose the drive current supplied to LEDs, and they can control junction temperature at the LED via thermal management.

Predicting the probability of failure of an LED array

So far, we have shown that lumen maintenance and catastrophic failures are two different kinds of LED behavior: they have different effects on a luminaire's visual appearance and on its performance; and the operating conditions in a luminaire affect the behaviors differently.

This means that luminaire designers need to be able to refer to discrete predictions for lumen maintenance and for catastrophic failure rates.

But as observed above, the rate of lumen maintenance and catastrophic failures combine to produce a decline in system light output over time. So as well as being expressed as discrete values, lumen maintenance and catastrophic failure rates also need to be expressed in combination.

It is possible to combine the two values to produce a probability of a single LED failing either through passing a lumen maintenance threshold, or through catastrophic failure. Such a probability curve is shown in Figure 13.

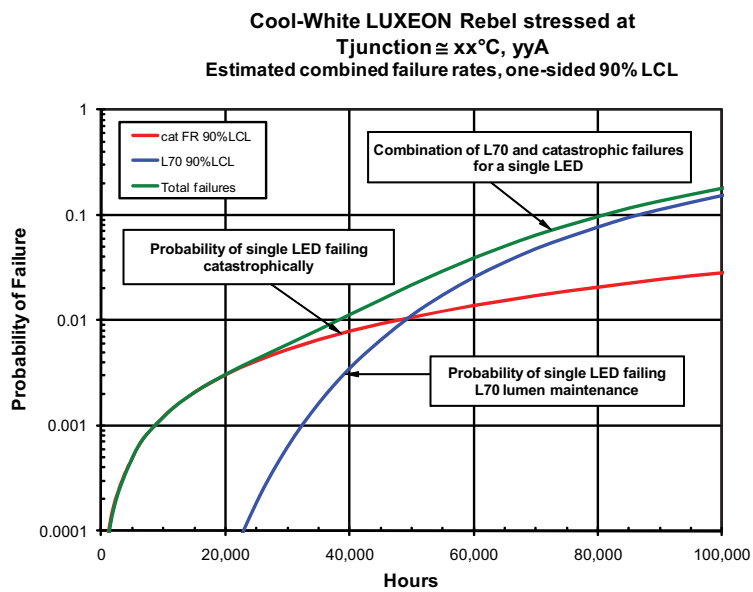

Figure 13. Combined lumen maintenance and catastrophic failure model.

But an LED light might contain an array or string of multiple LEDs. So the luminaire manufacturer needs to know how long the light can operate before the complete array's lumen output has fallen below its specified minimum (expressed as an Lxx figure for the complete array, where xx is a percentage of the array's peak light output). Decline in the array's output to Lxx will result from a combination of catastrophic failures in some LEDs, and gradual decline in output—the lumen maintenance effect—in the rest.

If all LEDs across all luminaires were assumed to fail at the same rate, the curve in Figure 13 could be used to predict the probability of failure of a complete array for any given operating conditions and Lxx threshold.

This is not what actually happens in reality. This is perhaps best illustrated by reference to a gambling analogy. Imagine you are holding a hand of 10 cards, which is known to contain one ace. Draw one card from the hand: the probability that it is an ace is 10%.

Now imagine you hold 60 hands of 10 cards, each hand containing one ace. Drawing one card from each of the 60 hands, the

probability that you will draw 6 aces is, in fact, 56%. There is a chance that you will draw no aces. There is even a one-in-thousand (0.001%) chance that you will draw 18 aces.

This gambling analogy describes a statistical concept known as 'binomial distribution', and it applies to the way failures are distributed within groups of LEDs, just as much as to the way in which aces are dealt from hands of cards.

Assume, for a single LED, a 10% probability of catastrophic failure under given operating conditions (the equivalent of one ace in a hand of 10 cards). A luminaire manufacturer uses this LED in luminaires that each contains an array of 60 LEDs (the 60 hands of cards above). Because failures follow a binomial distribution pattern, a 10% failure rate at the level of the individual LED does not mean that every one of the manufacturer's luminaires will have six failures—just as there is not a 100% probability of drawing 6 aces from the 60 hands of cards.

In fact, the gambling analogy shows that it's likely that 56% of the manufacturer's luminaires will contain 6 failures. Some of the arrays will contain none. One in every 1,000 luminaires will contain 18 failures.

It is now clear that using the combined Lxx failure model for a single LED (the graph in Figure 13) as a proxy for the probability of failure of a complete array of LEDs is flawed.

Fortunately, the semiconductor industry, the automotive industry and others have proven the validity of a practice known as the 'Monte Carlo method' to accurately predict the probability of system failure based on known component failure rates.

The Monte Carlo method works this way. Assume that a luminaire contains an array of 32 LEDs, used at given operating conditions that produce a probability x of catastrophic failure and a probability y of lumen maintenance failure. Each LED in the array could be characterized by two numbers: the time to catastrophic failure and the time to L70 light output. Thus, for each LED, it is possible to calculate the light output as a function of time by using the exponential light output model. At the time of catastrophic failure, the light output abruptly goes to 0. Then the system light output is simply the sum of the light output curves for each of the LEDs in the array. So the time to system Lxx occurs when the combined light output falls below this limit.

Now take a random sample of 32 LEDs: as the deck-of-cards example above shows, the sample might contain no catastrophic failures, one catastrophic failure, or more than one catastrophic failure. It might also contain a preponderance of high-performing LEDs in lumen maintenance terms, or a preponderance of low-performing LEDs—there is a distribution of lumen maintenance performance, as Figure 6 above shows. This particular random sample of 32 LEDs, with its combination of catastrophic failures and lumen maintenance, will cross the manufacturer's chosen Lxx threshold after a certain number of operating hours.

But if you take another random sample of 32 LEDs, the Lxx threshold could be crossed earlier or sooner, since the number of catastrophic failures could be different (as our deck-of-cards example again shows), and the preponderance of higher- or lower-performing LEDs (in lumen maintenance terms) could also be different.

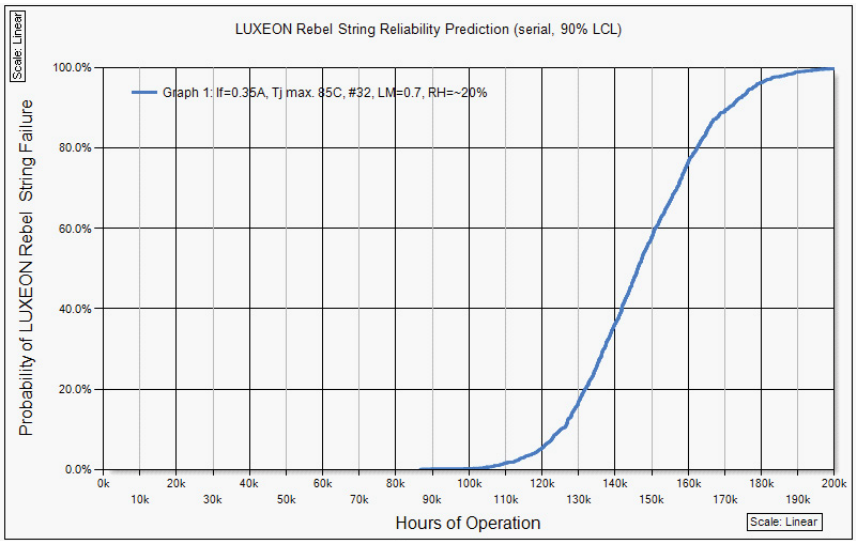

Figure 14. Monte Carlo simulation for a 32-LED system.

In fact, every random sample of 32 LEDs will perform slightly differently, producing a spread of performance across the population of 32-LED luminaires.

What the Monte Carlo method does is to take many such random samples of 32 LEDs, and plot for each one the point at which it crosses the system Lxx threshold. The curve joining these many points provides a model for predicting the probability of system Lxx failure. This curve can be displayed graphically (see Figure 14).

This graph, then, predicts the probability that any given combination of 32 LEDs will fail in terms of system light output—the combination of lumen maintenance failures and catastrophic failures—at the given operating conditions. This shows a spread of outcomes, from the worst performing array to the best performing array. A luminaire manufacturer can use this information to help determine, for instance, a sustainable warranty period based on a known number of LED array failures at the warranty's expiration.

And because Lumileds models for lumen maintenance and for catastrophic failure predict LED behavior for any combination of drive current and junction temperature, the model can determine the probability of system Lxx failure for any operating condition (within the data sheet range) and for arrays of any number of LEDs.

This system reliability approach:

- provides a comprehensive picture of LED performance at the system (luminaire) level. Unlike LED reliability measures commonly published today, it shows for any given set of operating conditions and size of luminaire how the worst luminaire will perform, how the best will perform, and the spread between them.
- informs investment and risk-management decisions. It enables luminaire manufacturers to accurately predict the percentage of units that will fail to survive their warranty period. Previous reliability models that model only for median performance place large, unforeseeable risks on the luminaire manufacturer, because they do not show how far short of median performance any individual luminaire is likely to fall.
- enables luminaire manufacturers to quickly and easily optimize designs for reliability and cost. The simplicity of the approach allows users to quickly evaluate many different choices for drive current, temperature, system size and light-output target. Designers can, for instance, avoid over-specifying systems that would maintain system light output for much longer than use-case assessments suggest was necessary.

We started with the assertion that the current lighting industry practice of taking LED lumen maintenance ratings as a proxy for a luminaire's lifetime rating was flawed. Figure 15 is an example that shows the potential commercial impact of this practice.

At a drive condition of 0.35A and a junction temperature of 85°C, the LEDs have a median L70 of 176,000 hours. Note from the lower left graph that there is a 15% probability of L70 lumen maintenance failure at 100,000 hours. So the manufacturer might set 100,000 hours as the warranty duration. As shown by the lower right graph, the catastrophic failure model shows that the LEDs when driven at 0.35A and at a junction temperature of 85°C have a probability of catastrophic failure of about 2% at around 100,000 hours. And in this example, the system failure probability curve produced by the Monte Carlo method shows that luminaires will perform better than individual LED lumen maintenance suggests—there will in fact be no system failures at 100,000 hours.

But the same approach when applied to a luminaire in which the LED junction temperature is 135°C is commercially disastrous. At a drive condition of 0.35A and a junction temperature of 135°C, the LEDs have a median L70 of 150,000 hours. Note from the lower left graph that there is a 20% probability of L70 lumen maintenance failures at 100,000 hours. So the manufacturer might set 100,000 hours as the warranty duration.

But Figure 16 shows that at the system level—rather than at the level of a single LED—that 30% of the arrays will have failed at 100,000 hours. As shown above in the lower right graph, the catastrophic failure model shows that the LEDs when driven at 0.35A and at a junction temperature of 135°C have a probability of catastrophic failure of about 8% at around 100,000 hours. This example shows that high operating temperatures are a strong driver for catastrophic failures, and these are the main reason that system light output rapidly drops below L70. The manufacturer now faces the commercially disastrous prospect of replacing a number of luminaires.

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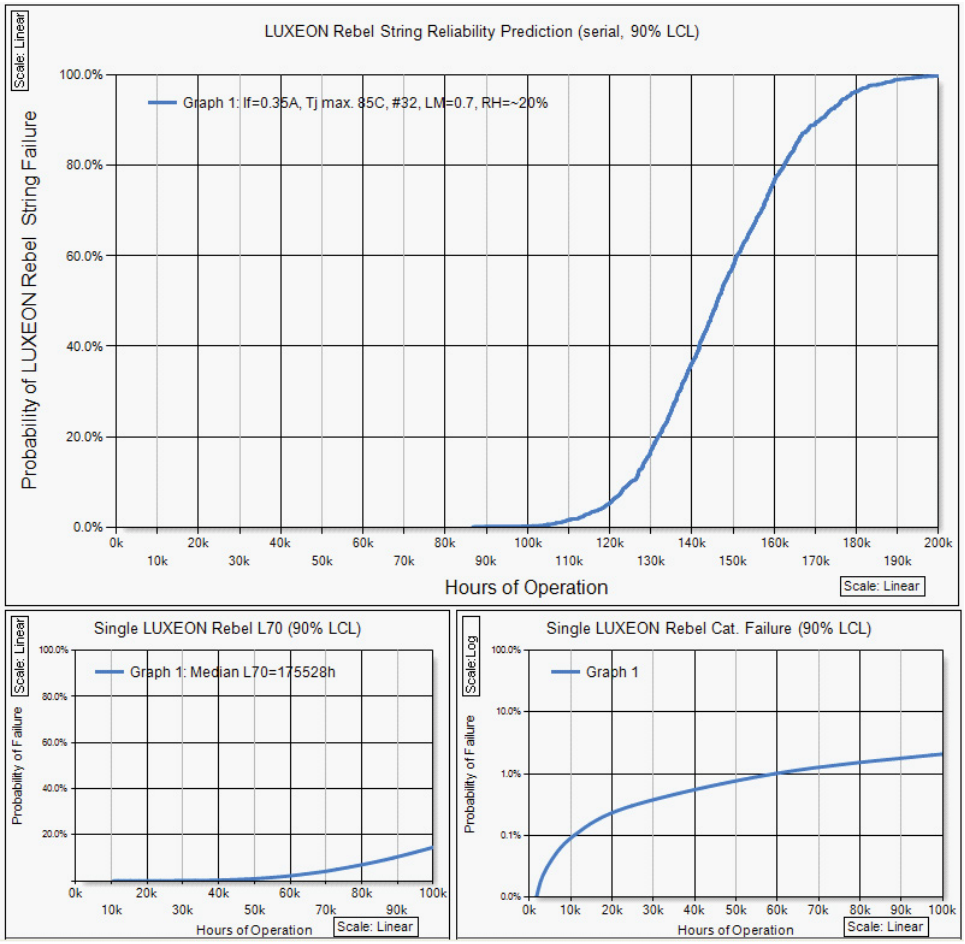

Figure 15. Top graph shows Monte Carlo simulation of 32-LED system.
Bottom graphs show lumen maintenance and catastrophic failure models for LED component.

All components of a luminaire affect system reliability. This approach predicts the long-term performance of arrays of LEDs. But the reliability of a luminaire is actually affected by the reliability of every single component it contains, including the LED array, but also the mechanical, electrical and optical parts. The weakest link breaks the chain, and in fact a luminaire is only as reliable as its least reliable component.

Experience shows that this is very rarely an array of LUXEON Rebel LEDs. The common causes of failure in LED lights are:

- driver module, which can either fail catastrophically or can cause the drive current to change over time
- electrical connections and solder joints, which tend to fail open, thus causing a complete string of LEDs to go dark
- secondary optics, which can degrade over time, reducing light output. (The rate of degradation is a function of the materials choices made by the luminaire manufacturer.) Light path changes also affect system light output, and weather and other environmental factors can affect the light path.
- inconsistencies of manufacturing (missing screws, etc.) can impair a thermal interface (thus increasing the system's thermal resistance) or a light path (thus reducing system light output).

Any increase in thermal resistance will affect junction temperature, which is a crucial factor in LED component reliability.

Analysis of the reliability of each of these components in a system, and the time-to-failure of each across a population of luminaires, should be carried out in the same way as for LEDs.

Such analysis should then be fed back into the LED selection and system design process, to ensure that the LED sub-system is not over-specified. For instance, for a given design, assume that the best-performing 95% of LED arrays will reach the Lxx threshold after 150,000 hours or longer. Assume again that analysis of the driver module shows that 5% of the modules will have failed after 50,000 hours, and as a result the manufacturer decides to warranty the luminaire for no more than 50,000 hours of operation.

The LED sub-system has therefore been specified to emit light, in 95% of the units manufactured, for at least 100,000 hours longer than the product's warranty requires.

The luminaire designer can then choose to perform 'what if?' analysis, to reduce the amount of over-specification of the LED sub-system. Achieving a better match of the LED array's predicted time-to-failure to that of the weakest component in the system can help to reduce the manufacturer's bill-of-materials cost and produce a luminaire that is more fit for purpose.

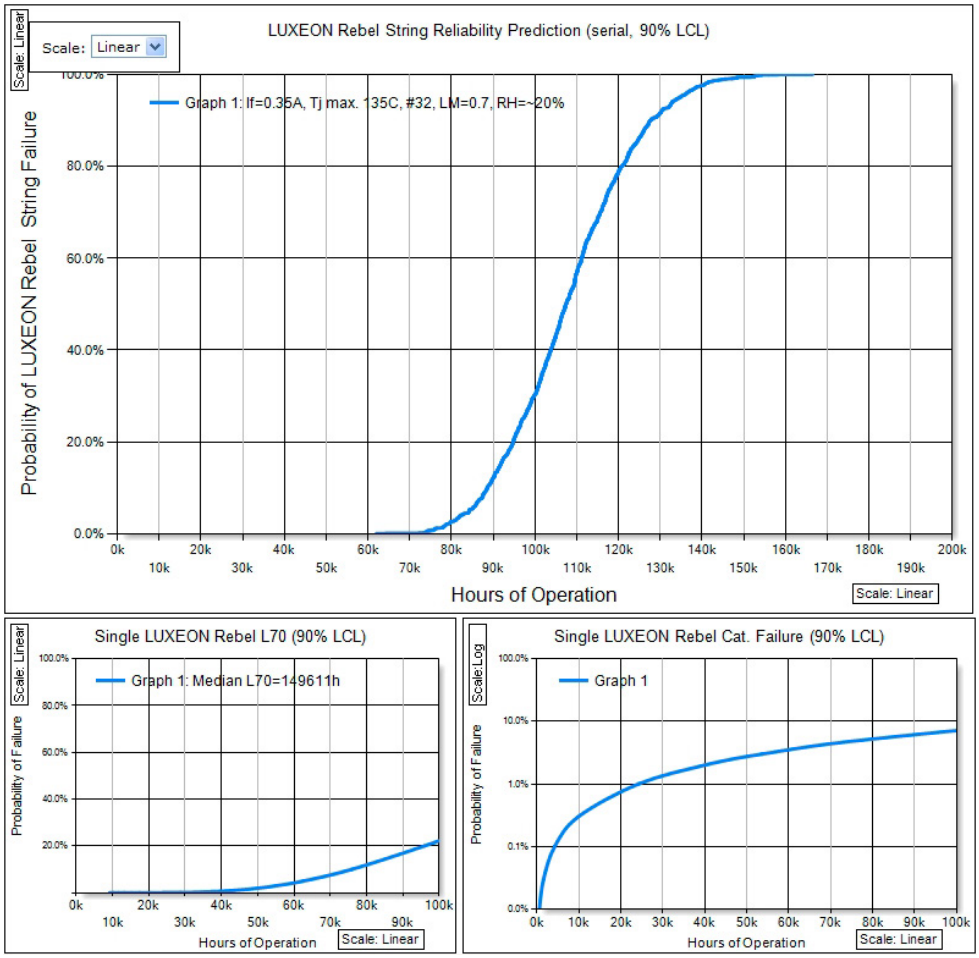

Figure 16. Top graph shows Monte Carlo simulation of 32-LED system.
Bottom graphs show lumen maintenance and catastrophic failure models for LED component.

An LED based luminaire or solution is a complex system comprised of many components each with their own behavior and expected performance over time. Because of the familiar lighting paradigm, light sources are usually considered to be the weakest link in the system and therefore garner the most attention. This is, in no small part, why standards activity has focused primarily on LEDs to date and because of this, LED manufacturers have a significant amount of data regarding the lumen maintenance and failure rates and modes of failure. It should be clear, however that in the new lighting paradigm, the light source, LED, is probably not the weakest link but in fact just one of a number of components whose lifetime must be understood. We hope that through our evaluation and explanation of both lumen maintenance and failure rates, the reader's understanding of LED lifetime is better understood along with the following concepts; Lumen maintenance is not a proxy for LED lifetime, the lifetime of an LED system is based on achieving minimum levels of light output, and lastly, by designing for reliability, luminaire manufacturers can maximized design, minimize costs and appropriately warranty their systems.

The purpose of this paper was to draw attention to the many aspects of LED reliability and not to convey specific data. Any charts in this white paper are for a specific LED technology only and can change at any point in time. Work with your Lumileds Sales Representative or Lumileds Technical Support Manager to tailor reliability predictions to your specific application.

About Lumileds

Lumileds is the global leader in light engine technology. The company develops, manufactures and distributes groundbreaking LEDs and automotive lighting products that shatter the status quo and help customers gain and maintain a competitive edge.

With a rich history of industry "firsts," Lumileds is uniquely positioned to deliver lighting advancements well into the future by maintaining an unwavering focus on quality, innovation and reliability.

To learn more about our portfolio of light engines, visit lumileds.com.

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