Realistic test approaches provide accurate LED-lifetime numbers

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LED technology has matured to the extent that it can be used for a variety of applications, from architectural lighting systems to medical diagnostic equipment, display systems, and streetlights. Some benefits of LEDs include long life, improved uniformity, reduced maintenance, promotion of vision at low light levels, and energy savings. However, despite their intrinsic long life, LED performance can deteriorate over time.

Environmental degradation factors include high temperature, humidity, solar radiation, current and cycling of these (references 1 and 2). Thermal load is the primary factor affecting the lifetime of LEDs in usage. Under temperature cycling, differences in coefficients of thermal expansion may cause loss of adhesion at the interfaces and cracks in the packaging material. It has been proven that weak adhesion strength makes the delamination expand faster and prevents resistance to multi-shocks.

Generally, heat is coupled with driven current. Increasing current generates more heat and induces worse electrical stress and thermal stress. The coupling effects of heat and current on the reliability of LEDs have been largely studied experimentally (references 3 and 4). Moisture concentration in packaging materials will increase gradually with the usage of LEDs. Mismatch for moisture expansion coefficients of packaging components can induce hygromechanical stress, potentially causing a reduction of the interfacial adhesion strength, and leads to delamination, similar to the effect of thermomechanical stress (Reference 5). The external parts of LED products designed for outdoor application are additionally exposed to solar radiation (a polychromatic source of UV, visible, and infrared radiation). UV radiation induces photochemical processes in most polymeric materials, promoting the degradation of mechanical properties of the system’s housing, and the reduction in transmittance of polymeric optical parts, such as the LED’s window. The visible and IR parts of daylight contribute to heat up unidirectionally the whole system, causing an additional mechanical stress that cannot be duplicated in heated cabinets (Reference 6). Other environmental stress factors, including atmospheric gases and pollutants, dust, salt water, mildew growth, and wind, may exert an influence, as well (Figure 1).
According to a review on the reliability of LEDs, the influencing mechanisms of manufacturing and operation on the reliability are not fully understood. Potential issues include deformation, voids, delamination, cracks, and impurities. These issues are generally attributed to improper choice of materials, incorrect handling and processes, nonoptimized structures, and excessive usage under harsh conditions. Failure modes for individual LED units are recognized at the chip level, at the interface chip/packaging material level, and at the packaging material level (references 1, 2, 7, and 8).

The housing of LED products for outdoor application must shelter the various electrical and electronic components (including the contacting part of the LED, the circuit board onto which the LEDs are mounted, and the controller board), mainly from mechanical shocks, rain, and solar radiation. It is often made of polymeric parts onto which the effect of solar radiation will be particularly relevant in the initiation of failure modes such as cracks, loss of gloss, whitening, and discoloration. Because these failure modes affect the safety, structural, and aesthetic properties, durability testing of the housing constitutes a relevant part of assessing the long-term reliability of an LED product.

Major manufacturers of LED video-display systems guarantee a lifetime of about 10 years in continuous use (75,000 to 100,000 hours) in any type of end-use environment. The performance criteria are brightness and lifetime, defined as the time to 50% of initial brightness. This statement implies that the various materials and parts used in the fabrication of the product must perform reliably during at least the same period. For instance, if the guaranteed lifetime of the LED’s brightness is 10 years, the system’s housing shall be designed to retain an acceptable level of safety, structural, and aesthetic properties for a minimum of the same period so that its lifetime will not be the limiting factor of the product’s lifetime. For obvious reasons, it is not possible to wait for years of outdoor or field exposure to find out whether a product will last. At best, manufacturers perform two to three years of outdoor exposure, which does not even back up half the warranty period in real conditions of use. Most often, manufacturers don’t even have any real-life or outdoor data at all, hoping that their product will last as stated in the warranty.
The traditional approach to evaluate the reliability of electronic components, parts, or full products is to perform ALTs (accelerated life tests), such as described in some international or military standards (references 9 and 10). These procedures consist of several tests involving one or two individual stress factors applied at near natural levels, resulting in modest acceleration. HALT (highly accelerated life test) and HASS (highly accelerated stress screening) are types of qualitative ALTs widely used by the electronics industry (references 11 and 12). These tests—temperature cycling, humidity-freeze, damp heat, or pressure cooker, to cite the most common—are meant to screen for major material, design, and manufacturing flaws that would likely result in premature “infant mortality” failures (Reference 13). In other words, HALTs are not meant to predict lifetime; they attempt only to force failure by any means possible because, very often, they use conditions that are not found in any real climate. Although ALT and HALT may be suitable for assessing the reliability of electronic products in enclosed or indoor environments, they do not take into account the complex and often synergistic interaction between solar radiation, temperature, and humidity encountered in outdoor environments. To address long-term durability and wear-out issues, true accelerated environmental life tests are needed. Accelerated weathering testing provides within a reasonable time frame an acceptable level of assurance that the tested products will meet performance and warranty expectations. For more than 90 years, weathering testing has been successfully relied upon by many industries (for example, automotive, plastics, paints and coatings, textile, building, packaging, food and beverages, and wood treatment) to help reduce premature product failure and save related cost (Reference 14). During that time, much has been learned about materials degradation and proper accelerated weathering approaches. Today, a range of technologies and methods are available to carry out laboratory and outdoor weathering testing, as well as to measure property changes, interpret and correlate the weathering data, model the aging behavior, and even predict lifetime (Reference 15).

Accelerated weathering tests aim at inducing as realistically, precisely, and quickly as possible the degradation modes resulting from the time-dependent, repeated application of combined environmental stresses delivered in their natural short and long-term cycles (Reference 16). The intents of such tests and of screening “infant mortality” tests are therefore very different from each other (Figure 2).

To find out how electrical products designed for outdoor use react to environmental stresses in an acceptable time frame, as well as for quality testing during series production or for the future development of similar designs, a carefully designed test program can prove helpful. A test program consists of a set of individual and logically linked test methods intended to reproduce the response of a product to a specific environmental stress or combination of environmental stresses.

At the heart of such a test program resides an accelerated weathering test. As all degradation mechanisms responsible for field failures may not be equally accelerated by the core laboratory weathering test, complementary tests may be added to the test program. For instance, UV exposure and salt-spray corrosion may be run prior to the main accelerated weathering test to jump-start specific degradation modes that may be revealed during the laboratory weathering phase. (H)ALT
may also be useful for material-screening purposes or to grossly check for individual failure modes in a quick time frame. The main steps to develop a sound weathering test program are summarized here (references 16 and 17).

The performance criterion or criteria characterizing the lifetime of the product is stated (for example, the luminous efficiency and the spectral distribution in the emission range), and the maximum acceptable performance change clearly defined. This could, for example, be no more than 15% loss of initial brightness after five years of continuous use or a yearly loss lesser than 3% during the first five years. If the product’s loss of performance is not linear in time, both definitions of performance level are not equivalent.

The test program shall be designed to reproduce the maximum acceptable performance change, either through running the test over an equivalent five years in service, adding an arbitrary security margin of 20% (one year), or through running the test over a portion of the expected lifetime and extrapolating results based on existing experience with the product in real life. In both cases, an acceleration factor of the test program in real life needs to be estimated, at first theoretically (as explained below), then adjusted or confirmed on the basis of experimental data.

This tool is used to learn about the specific degradation mechanisms and failure modes affecting the normal system operation and to understand the type and range of environmental degradation factors that contribute to failure. These may be environmental stresses, but also weaknesses in the product design, such as inappropriate edge sealing.

The average and boundary (worst-case) values of the environmental stressors recognized in the modified FMEA (failure mode and effects analysis) will be researched to support the choice or the design of the laboratory weathering test method. Among possible end-use environments, outdoor locations experiencing a hot, humid tropical/equatorial climate are believed to exert the harshest end-use conditions on electronic products for outdoor use, combining high levels of solar radiation, temperature, and humidity. Locations with a hot, arid climate also produce severe end-use conditions, combining high solar radiation and temperature levels and marked diurnal temperature variations. Both cases of extreme weather conditions are discussed here. For some more climate-specific applications, the research could be extended to other harsh weather conditions, such as extremely cold climates or marine environments.

To determine the worst-case places experiencing a tropical/equatorial climate (according to the Köppen-Geiger climate classification (Reference 18)) as an example, a possible approach is to compare the yearly averaged levels of solar radiation; mean and maximum temperature; mean, minimum, and maximum relative humidity; and cumulated precipitation that can be obtained from a climate research (Internet-based meteorological resources, such as www.wetteronline.de, www.wetter.com, and a supplementary material published with the paper from MC Peel et al referenced above, as well as Atlas weather and radiation summary reports). When comparing solar radiation, all four locations experience similar yearly irradiation levels, based on the results obtained with the Atlas CESORA (Calculation of Effective Solar Radiation) proprietary tool, so this factor cannot be used as differentiator. Given a certain set of parameters as input, the program can calculate the resulting solar irradiation on a tilted or horizontal surface according to two accepted scientific models of sunlight passing through the atmosphere (SPEKTRA and SMARTS). More information about CESORA can be obtained here and more information about SMARTS can be obtained here.
Relative humidity and temperature data were plotted on a graph (Figure 3). For the four hottest locations—Singapore, Xisha Dao, Bangkok, and Chennai—the average RH level ranges from 70 to 83%, while the average temperature difference is 1.5°C or less. In Bangkok and Chennai, the average maximum temperature extends up to 33°C, but no information is available in the frequency of occurrence. Singapore and Xisha Dao have the highest average relative humidity, with the lowest yearly variation.

When looking at the average annual precipitation for these four locations Figure 4, Singapore receives by far larger annual levels of precipitation. From there, one can refer to Singapore as delivering worst-case temperature and moisture (under both vapor and liquid phases) conditions among the tropical/equatorial locations considered in this study.
Several active weathering standards and test methods aim at simulating end-use environments such as found in tropical/equatorial or hot, arid climates in an accelerated manner (Reference 19). These tests may use either constant or varying temperature and humidity conditions, under constant or intermittent illumination. These types of cycles may be more or less appropriate for different types of materials/components/products, depending on their sensitivity to moisture, temperature, and UV radiation, so specific adjustments may be needed for the intended application and end-use climate.

One or more test methods shall be selected for their ability to reproduce as closely as possible the effects of the stress factors recognized in the FMEA during the real life of the product using the results of the climate research, in particular the worst-case weather conditions for each type of climate. If no existing test method seems appropriate, it will be newly designed. Experience obtained from previous tests may also greatly help the choice/design of the test cycle.

For products consisting of the association of various materials, the natural diurnal cycling of temperature will be an important wear-out factor. A realistic test to reproduce in an accelerated manner the naturally occurring thermomechanical stress effect may consist of two dwelling phases at constant temperature (for example, at +65°C and -20°C), relative humidity, and irradiance. Two intermediate phases would ramp up and down temperature between these two values within a reasonably short period of time (between 90 and 150 minutes, for instance) to generate an intensified though realistic thermomechanical stress at the various material interface. The temperature profile and light cycle of this so-called solar-thermal humidity freeze test is shown in Figure 5 (Reference 20).
A DOE (design of experiment) for stress/response analysis of individual factors of degradation may be planned to select the most appropriate complementary tests to the core weathering test. It will also help confirm the main failure modes recognized during the modified FMEA (Reference 21).

A DOE will typically include a HALT, such as temperature cycling and humidity freeze tests to check the effects of low temperatures and icing on the product or damp heat to evaluate the sensitivity of a product to moisture at elevated temperature. The validation phase consists of checking that the test program correlates with the end-use environment it simulates and to refine or adjust the theoretically determined acceleration factors.

A crucial aspect of any accelerated test program is to initiate an outdoor exposure series of real products. Although nobody wants to wait for several years to find out whether a product will perform as expected in real life, results achieved from the field provide invaluable information on how and when products are likely to fail, as well as support the validity of the test method, and can be used for fine-tuning of the test-method parameters.

Therefore, aside from running the test program, it is recommended to plan and initiate a series of outdoor exposures at relevant locations; for instance, in Miami, FL, a benchmark for tropical climates, and Phoenix, AZ, a benchmark for hot, arid climates (Figure 6). The timeline to obtain outdoor results will condition the duration of the validation phase. Any deviation of the laboratory results from the real-life or outdoor results should prompt reconsidering the test program, carrying out more pre-testing to check whether relevant degradation modes have been overlooked, or both.
The expressions and calculations described below apply to estimating the acceleration of the wear-out mechanisms (other than thermal fatigue), causing loss of performance due to increased levels of temperature and irradiance. It does not address the wear-out mechanisms resulting from moisture effects, or electrical and mechanical stresses. This estimation relies on comparing the rate of thermally activated degradation processes that obey the Arrhenius equation (References 22 and 23). This approach is valid as long as the dominating degradation mechanism remains the same in the temperature range covering end-use and laboratory conditions (Reference 24). The analytical expression is given by Equation 1:

$$\frac{k_1}{k_2} = e^{\frac{E_a}{R} \left( \frac{T_2}{T_1} - 1 \right)} = AF$$  \hspace{1cm} (1)

where \(k_1\) and \(k_2\) are the rate constants of the process in test conditions 1 and 2, \(E_a\) is the apparent activation energy of the process (in J.mol-1), \(R\) is the gas constant (8.314 J.mol-1.K-1), \(T_1\) and \(T_2\) are the absolute temperatures of test conditions 1 and 2 (in K), and AF is the acceleration factor.

As in the presence of light, most polymeric materials undergo photothermally activated processes, a modified form of the Arrhenius include the contribution of light, expressed in Equation 2 (Reference 25):

$$\frac{k_1}{k_2} = \left( \frac{l_1}{l_2} \right)^\alpha e^{\frac{E_a}{R} \left( \frac{T_2}{T_1} - 1 \right)} = AF_L \cdot AF_T = AF$$  \hspace{1cm} (2)

where \(l_1\) and \(l_2\) are the effective irradiances in test conditions 1 and 2, \(\alpha\) is a material-dependent coefficient, \(AF_L\) is the acceleration factor resulting from varying the effective irradiance (ratio of irradiances), and \(AF_T\) is the acceleration factor resulting from varying temperature (ratio of Arrhenius terms).

Some models based on the Arrhenius equation incorporate a term relevant to the possible effect of moisture in tests involving high levels of relative humidity at high temperature, such as a damp heat test (References 26 and 27).

Equations 1 and 2 require the apparent activation energy of the overall degradation process as input data. It can be either assumed from literature data or experimentally estimated through a series of oven testing at a minimum of three temperature levels (for example, 60, 75, and 85°C) by plotting the logarithm of the time after which a certain performance change is obtained against the
reciprocal absolute temperature. When daylight is a degradation factor, it is recommended to carry out instead a weathering test at three different temperature levels under illumination simulating daylight constant irradiance in order to determine the value of an activation energy for photothermally activated processes. If the three points are on the same straight line, then the degradation process most likely follows an Arrhenius dependency in the experimental temperature range. The activation energy is proportional to the slope of the line. It is common practice to assume the same activation energy value for lower temperatures, such as the operating temperature for the product in real use.

**Equations 1** and **2** require defined input values for temperature and irradiance, as temperature and irradiance constantly vary outdoors. While it is justified to use the arithmetic mean of irradiance in test conditions 1 and 2, it is not possible to use the same approach for temperature due to the exponential dependency of the rate of degradation processes in the Arrhenius equation. An acceptable alternative is to calculate an effective temperature, $T_{\text{eff}}$, that is a constant temperature, which would produce the same amount of thermally driven damage as a varying temperature in actual conditions of use (**references 23** and **28**). The term equivalent temperature ($T_{\text{eq}}$) is sometimes used (**Reference 29**).

In outdoor conditions or, more generally, in the presence of photochemically active light, the definition of effective temperature becomes a constant temperature that would produce the same amount of photothermally induced damage as a varying temperature after exposure to the same amount of daylight (**Reference 30**). Detailed climatic data are necessary to calculate these two types of effective temperature, whose expression is given in **equations 3** and **4**, with the help of a conventional spreadsheet application:

\[
\sum_t \Delta t = \sum_t \exp \left[ \frac{E_a}{R} \left( \frac{1}{T_{\text{eq}}} - \frac{1}{T_t} \right) \right] \Delta t \quad (3)
\]

\[
\sum_l I_t \Delta t = \sum_t l_t \exp \left[ \frac{E_a}{R} \left( \frac{1}{T_{\text{eff}}} - \frac{1}{T_t} \right) \right] \Delta t \quad (4)
\]

where $\Delta t$ is the time interval between measurements, $T_{\text{eq}}$ is the equivalent/effective temperature relative to thermally driven processes only, $T_{\text{eff}}$ is the irradiance-weighted effective temperature relative to photothermally driven processes, and $T_t$ and $I_t$ are, respectively, the measured material temperature and incident effective irradiance at each interval.

Although the protocol for the determination of such values applied to the case of photovoltaic panels is detailed elsewhere, the approach remains valid for any type of material or product, provided the temperature and, when light is involved, the irradiance or radiant exposure are monitored over the full exposure period or a significant portion of it (**references 25** and **31**).

A Coffin-Manson model or the alternative Norris-Landzberg model may be used to theoretically estimate the magnitude of generated thermal fatigue stress by comparison to real-use conditions (**Reference 32**). When written in terms of acceleration factors, these models predict that the acceleration is proportional to the square of the ratio of magnitudes of temperature change in accelerated and in end-use conditions, according to **Equation 5**, related to the simplest Coffin-Manson model:
where \( A_{CM} \) is the acceleration factor for number of cycles, \( \Delta T_A \) is the thermal cycle temperature change in accelerated environment (in K), \( \Delta T_U \) is the thermal cycle temperature change in use environment (in K), \( N_{fU} \) is the number of cycles to failure at use temperature change, and \( N_{fA} \) is the number of cycles to failure at accelerated temperature change.

**Equation 5** can also be written as follows:

\[
N_{fA} = N_{fU} \cdot \left( \frac{\Delta T_U}{\Delta T_A} \right)^2
\]  

The values for \( N_{fU} \) and \( \Delta T_A \) can be easily obtained. Assuming that a complete thermal cycle takes 24 hours, \( N_{fU} \) is the minimum number of days during which the product is expected to perform without failure. Assuming a 10-year lifetime, this gives \( N_{fU} = 365 \times 10 = 3650 \) cycles. Using the temperature values of the two dwelling phases of the hypothetical dynamic test cycle described above (+65°C and -20°C), \( T_A = 85 \text{ K} \).

The determination of the magnitude of temperature change in various end-use conditions, \( T_U \), requires detailed climatic data. Such data are available at Atlas' outdoor exposure sites in Miami and Phoenix, in particular for temperature sensor painted in black (so-called BPT, Black Panel Thermometer), which gives a value close to the maximum temperature achievable during daytime by any colored object. Although the temperature is measured and recorded every minute, 10-minute parsed data were used to calculate the maximum daily variation of temperature (also referred to as DTR, diurnal temperature range); that is, the difference between the maximum and minimum temperature measurement over 24 hours for each day between 2005 and 2010. (Although detailed climatic data are not publically available, Atlas monthly weather summary reports can be freely downloaded [here](#).) Despite differences in the monthly DTR between Miami and Phoenix, the yearly averaged DTR for a BPT at an angle of 5° oriented south is the same for both locations, around 34K. Given the variability of monthly DTRs over a year, especially in arid locations such as Phoenix, a more precise calculation would consider the average of the squared monthly averaged DTRs instead of the squared yearly averaged DTR, which is not our purpose here.

Applying **Equation 6**, \( N_{fA} = 3650 \times (34/85)^2 \approx 584 \) cycles of temperature change in accelerated conditions are necessary to produce the same extent of thermomechanical stress as experienced by the product after 10 years of real life in Miami and Phoenix. Assuming a 120-minute accelerated cycle, 584 cycles would require 1170 hours, or 49 days.

**Conclusion**

The constantly expanding indoor and outdoor applications for LEDs should compel producers to back up their warranty statement by producing and correlating laboratory and real-life data. The lifetime criterion is limited to the brightness level of the LED system, for which extensive laboratory testing results are available. However, this gives no guarantee that the various structural and electronic parts of a product will not cause its failure before the brightness reaches its lowest acceptable limit. There is currently no standardized procedure available to demonstrate the lifetime of complete products.
This paper introduced the basic rules of sound weathering-test-program development specifically tailored to material, performance requirements and application as an important step toward high testing quality, based on an approach developed and used by plastic-related industries for many years. At the heart of any such test program is an accelerated, relevant, and precise laboratory-weathering test protocol meant to reproduce the degradation modes and related changes in performance occurring in any given end-use environment. Because there is no single end-use environment, specific “acceleration factors” for any laboratory weathering test method are highly variable and dependent on materials, product design, manufacturing quality, and degradation mechanisms. Although it is possible to calculate theoretical acceleration factors, precise correlation to expected performance ultimately requires validation with long-term outdoor- or field-exposure data for the specific LED product design.

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