LED Driver Lifetime and Reliability

In recent years, LED based lighting technology as well as the number of applications that have embraced them has advanced rapidly. This is primarily because LEDs bring several advantages to the lighting industry, including high efficiency, durability, environmental friendliness and reduced maintenance requirements due to their superior life. All of these factors translate to energy and maintenance savings, and overall reduction in the cost of ownership over the product's lifetime.

High-power LED modules typically comprise of an array of LEDs soldered to a copper board that is separated from a heat sink by an electrically isolating but thermally conductive material. These LED arrays are powered by an LED driver, which could be either configured as a constant current source or as a constant voltage source, depending on application requirements. In most applications, these drivers are connected to the AC line on their input side. Also, their primary and secondary sides could be isolated depending on the application. Like other power converters, the LED drivers consist of several semiconductor switches, magnetic elements, passive capacitors, resistors and other active elements. All these electronic elements raise an important question for LED applications: *While LEDs themselves are extremely reliable and have a long lifetime, are the power electronics based LED drivers capable of providing the required current/voltage input to the LEDs over their whole life?*

Figure 1

In this paper, our aim is to address the above question in general and especially for the *Xitanium* family of LED drivers developed by Philips Lighting. We will describe some of the design guidelines and strategies that we use to maximize the LED drivers' lifetime and reliability, so that it does not become a bottleneck in the applications of LED based outdoor lighting.

Definitions related to Reliability and Lifetime:

Before proceeding into the guidelines for design of reliable LED drivers, it is important to understand the definitions related to the lifetime of electronics products, in general. Reliability experts often describe the reliability of a population of electronic products using a graphical representation known as the *Bathtub Curve*, as illustrated in Figure 2. The Bathtub Curve can be divided into three periods. The first is an initial period of infant mortality, where the defective/weak products fail. This is followed by the normal life of the product with a low and relatively constant failure rate. Following this is the final period of the product lifetime where wear-out mechanisms of the product kick in and the failure rates increase.

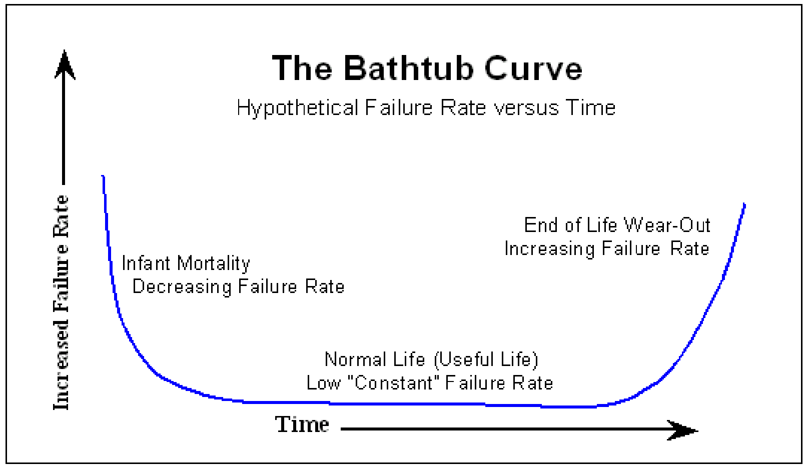

Figure 2

It is important to understand that the Bathtub Curve does not depict the failure rate of a single item, but describes the relative failure rate of an entire population of products over time. Some of the units will fail during the infant mortality period; others will last till the wear-out period while a few of the units will fail during the normal life. Reliability deals with random failures in a population of products and is expressed in terms of rates, such as *Failures in Time* (FIT) or *Mean Time to Failure* (MTTF). On the other hand, lifetime refers to the length of time that a single product may be expected to function properly before a known wear-out mechanism renders the product unfit to use. Lifetime is typically expressed in hours. For instance, a lifetime of 100,000 hours implies that under normal operating conditions, a typical product would be expected to last for 100,000 hours before failure. On the other hand, an MTTF of 100,000 hours means that if we look at a population of 1000 units, one could expect a random failure every 100 hours. In other words, the MTTF can be expressed as

$$MTTF = \frac{Total\ Operating\ Time}{Number\ of\ Failures}$$

The MTTF value can be interpreted in several ways:

- *If a large number of units are considered, only 37% of their operating times will be longer than the MTTF figure.*
- *We can say that the unit will work for as long as its MTTF figure with a 37% Confidence Level.*
- *From the equation for R(t) below we calculate that at 3 years (26,280 hours) the reliability is approximately 0.95, i.e., if such a unit is used 24 hours a day for 3 years, the probability of it surviving that time is about 95%. The same calculation for a ten year period will give R(t) of about 84%.*

Reliability Prediction Models:

Mathematically, failures in LED drivers (and other electronic circuits, in general) can be described by an exponential distribution:

$$R(t) = e^{-\rho t} = e^{-\frac{t}{MTTF}}$$

where the failure rate ρ is basically the inverse of the MTTF and can be expressed as

$$Failure\ Rate\ (\rho) = \frac{1}{MTTF}$$

The failure rate can be estimated using reliability models such as MIL-HDBK-217F and/or Telecordia SR 332. These models relate the statistical failure rate data of the individual components, operating temperature, voltage, power and ripple current (for electrolytic capacitors) to determine the overall statistical failure rates. The choice between the two models depends on the end application. The Telecordia SR 332 model is applicable to telecommunications applications. Their predictions are limited to component temperatures <65 ˚C. On the other hand, the MIL-HDBK-217F models are applicable to the military and other commercial applications. Their predictions are valid for components operating <125 ˚C. For some applications, the difference between the predictions of the MIL-HDBK-217F model has been shown to be about 20% more conservative than those of the Telecordia SR 332 model.

Because the components within the *Xitanium* LED driver could operate at temperatures above 65 ˚C, the MIL-HDBK-217F model is used for estimating the failure rate. According to the MIL-HDBK-217F model, the failure rate of the overall LED driver are obtained from the failure rates of the individual components of the driver and can be expressed as follows:

$$\rho = \sum_{i=1}^{n} \left(\rho_{ref}\pi_V\pi_I\pi_T\right)_i$$

where ρ_{ref} is the failure rate of the i^{th} component under the reference condition and are obtained directly from the vendor, π_V is the voltage dependence stress factor, π_I is the current dependence stress factor, π_T is the temperature dependence stress factor, and n is the number of components. The stress factors can be obtained from IEC 61709 Clause 7 and are expressed in the following table:

Voltage dependence stress factor (π_V)	$\pi_V = e^{C_3\left(\left(\frac{V}{V^*}\right)^{C_2} - \left(\frac{Vref}{V^*}\right)^{C_2}\right)}$ where V is the operating voltage of the component, $Vref$ is the reference voltage, V^* is the rated voltage, and C_2, C_3 are constants, which are described in IEC 61709 (for individual components)
Current dependence stress factor (π_I)	$\pi_I = e^{C_4\left(\left(\frac{I}{I^*}\right)^{C_5} - \left(\frac{Iref}{I^*}\right)^{C_5}\right)}$ where I is the operating voltage of the component, $Iref$ is the reference voltage, I^* is the rated voltage, and C_4, C_5 are constants, which are described in IEC 61709 (for individual components)

Temperature dependence stress factor (π_T)	$$\pi_T = \frac{Ae^{E_{a1}z} + (1-A)e^{E_{a2}z}}{Ae^{E_{a1}z^*} + (1-A)e^{E_{a2}z^*}}; \quad z = \frac{1}{k_0}\left(\frac{1}{T_{amb\_ref}} - \frac{1}{T_2}\right); \quad z^* = \frac{1}{k_0}\left(\frac{1}{T_{amb\_ref}} - \frac{1}{T_1}\right)$$ where A is a constant; E_{a1} and E_{a2} are activation energies, $k_0 = 8.616 \times 10^{-5}\ eV/K$; $T_{amb\_ref} = 313\ K$; T_1 is the reference temperature in degree K, and T_2 is the operating temperature in degree K. All the constants can be obtained from IEC 61709 (for individual components).

There are two key assumptions in determining the failure rates:

– All the components are past their infant mortality period (please refer to the bath tub curve in Figure 2)

– All design guidelines are followed and that the components operate within the derating rules.

Designing for Long Lifetime and High Reliability:

Designing the most reliable product that lasts for the longest lifetime while also meeting the constraints of cost, size, time to market etc. among other factors is a challenge for every product designer. The *Xitanium* LED drivers are developed through a tightly controlled design and development process, where the quality of product is evaluated at each milestone and activities to realize deliverables (and guidelines on how to perform such activities) are clearly defined. A snapshot describing the overall development process is illustrated in Figure 3.

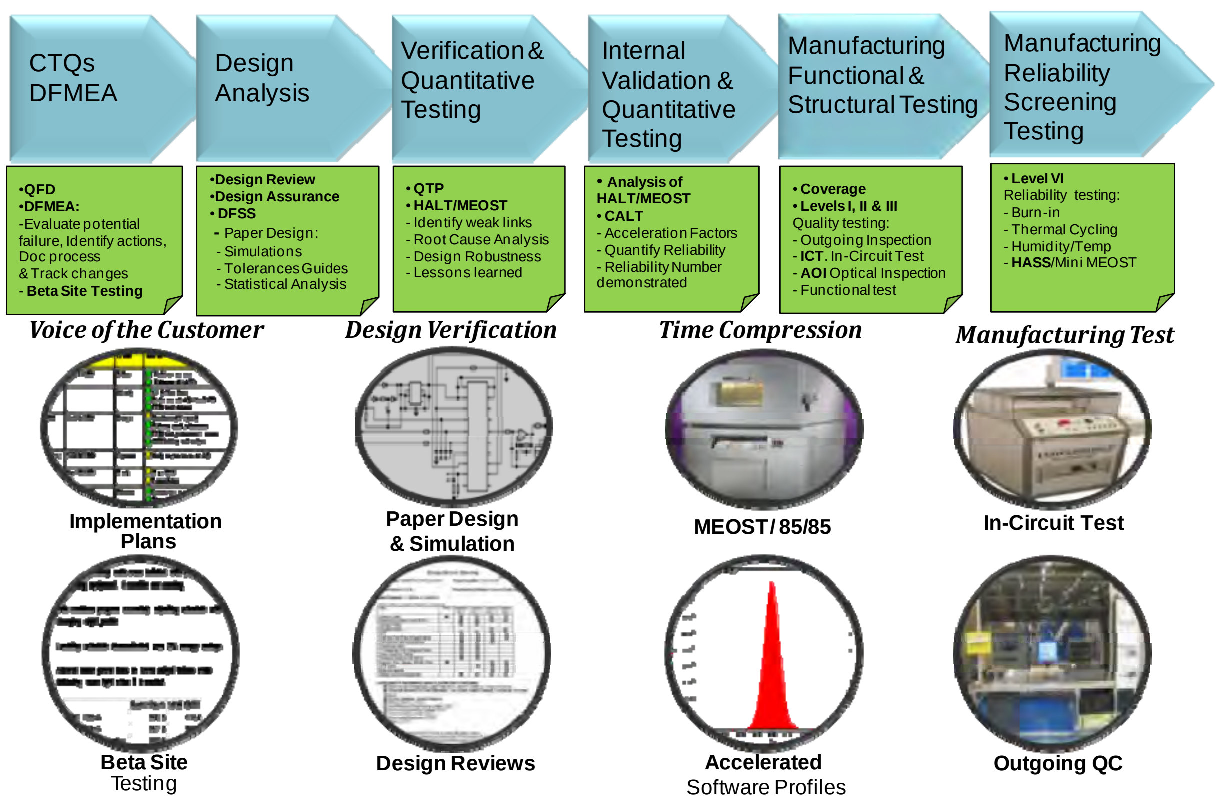

Figure 3

Key factors that are taken into account to develop the most reliable products are described in the following paragraphs.

Topology Selection: For LED drivers, the first issue is the selection of the most robust power conversion topology given the constraints of power, size, cost etc. For instance, while a flyback based topology may be suitable for low power/low voltage applications because of low parts count, with increase in the operating power, a two stage topology might be more suitable from the operating stress and power loss standpoint. Also, soft-switching LLC based topologies might also be used to further reduce the switching losses of the semiconductor switches; thereby further improving efficiency and reducing power loss.

System Efficiency: System efficiency (or power loss) has a direct and significant impact on the reliability and lifetime of an LED driver. This is because all of the power lost is dissipated as heat within the driver. This leads to increase in the temperature of the components within the driver. This means that if the power dissipated in the driver is high, the components within the driver operate at a higher temperature and vice versa. The reliability of components reduces as their operating temperature increases. Therefore, a driver operating with higher efficiency can have a significantly improved lifetime and reliability compared to a driver operating with lower efficiency.

Additional Protection Mechanisms: In addition to designing for lower power losses, the *Xitanium* LED drivers also have a high-temperature roll-off capability. If the case temperature of the driver exceeds a certain value due to abnormal operating conditions, the output current is reduced. This in turn reduces power dissipation and hence the temperatures of the internal components of the driver are not allowed to increase beyond a certain value. Since the operating temperatures of components have a direct impact on their failure rates, this feature allows us to enhance the reliability and lifetime of the *Xitanium* drivers. Additional protection schemes are also in-built into the driver hardware to enhance its reliability. For instance, to protect the driver against line surges during lightning strikes etc., additional surge suppressors are added.

Component Selection: Having decided on the right topology that yields the highest efficiency (for a given application), the next challenge is the selection of the components. For the *Xitanium* drivers, each and every component is carefully chosen and passes through extensive design qualification, testing and internal long term reliability tests. An extremely careful supplier selection process and long term relationship with the suppliers, ensures that only the best of the components are used in the *Xitanium* drivers. From a design point-of-view, careful analyses of component stresses and adequate derating of the components ensures a highly reliable LED driver that is capable of achieving industry-leading lifetimes. For instance, electrolytic capacitors are operated with about a 20% operating voltage margin, while the semiconductor devices are operated with a 10-20% operating voltage margin. Also, careful attention is given during the design phase to ensure that all of the components operate well within their maximum temperature ratings.

Lifetime Calculations: Having selected the components using the design guidelines described above, it is important to determine the components that are most likely to fail. Similar to other power converters, for LED drivers as well, the component most likely to fail is the electrolytic capacitor. The electrolyte in the capacitor will vent over time as a function of the operating temperature of the capacitor. Therefore, the lifetime of the driver can be directly derived from the lifetime of the electrolytic capacitor. The operating temperature of the capacitor is a function of the case temperature (which again depends on the power dissipated by the driver and therefore, the driver's efficiency) of the capacitor and the internal heating within the capacitor caused due to the ripple current flowing through it. The typical equation for the lifetime of the capacitor operating at a certain ambient temperature, L_T is given by

$$L_T = kL_0 2^{\frac{T-T_0}{10}}$$

where k is a factor that depends on the ripple current flowing through the capacitor;

T is the temperature at which the capacitor operates;

L_0 is the lifetime of the capacitor at the rated case temperature T_0.

The equation above shows that every 10 °C drop in the operating temperature of the capacitor doubles the lifetime of the capacitor. Figure 4 illustrates how for a 150W *Xitanium* driver, the lifetime of the overall LED driver (which is derived from the lifetime of the electrolytic capacitor) varies with the Driver case temperature. Here, the relationship between the case temperature and the temperature of the electrolytic capacitors is obtained through careful thermal measurements. For the lifetime calculations, it is assumed that the temperature difference between the capacitor and the case is always constant.

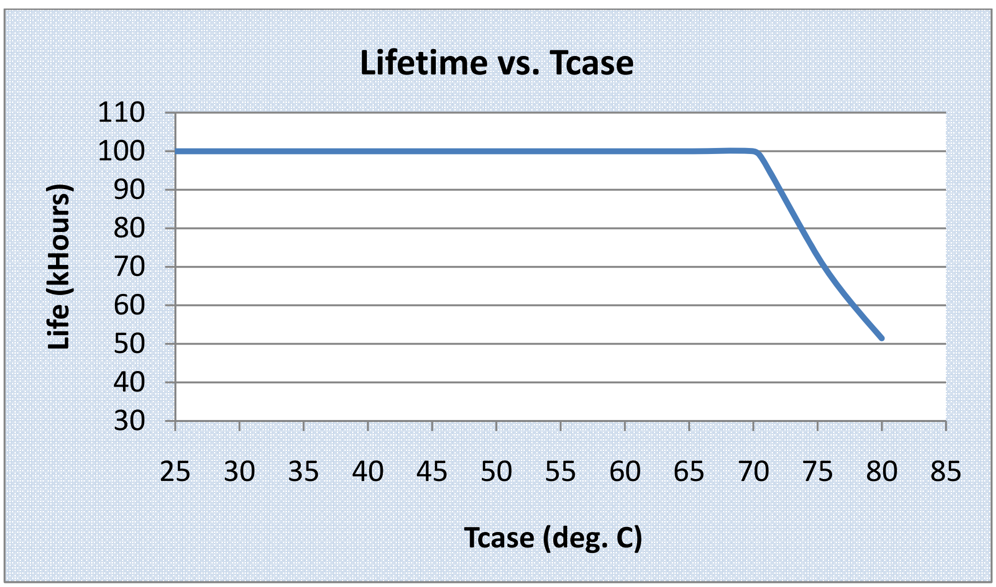

Figure 4

MTTF Predictions: While the lifetime of the LED driver depends on the component that is most likely to fail, the failure rate of the driver depends on all the components within the driver. As mentioned in an earlier section, the MIL-HDBK-217F reliability model is used to predict the theoretical failure rate of the *Xitanium* LED drivers. For a typical 150W *Xitanium* LED driver operating at a case temperature of about 50 °C, a theoretical failure rate of 538 PPM/1000 hours and a MTTF value of approximately 1.86 million hours is obtained. Figure 5 illustrates how the number of failures of the LED driver varies with time.

Please note that for the calculation, worst case electrical stresses are assumed to obtain a conservative estimate of the LED driver MTTF. If more realistic values are assumed, higher MTTF values can be expected. Also, these calculations assume a typical operating temperature. If the operating temperatures were higher, the stress levels on the driver components would increase leading to increased failure rates.

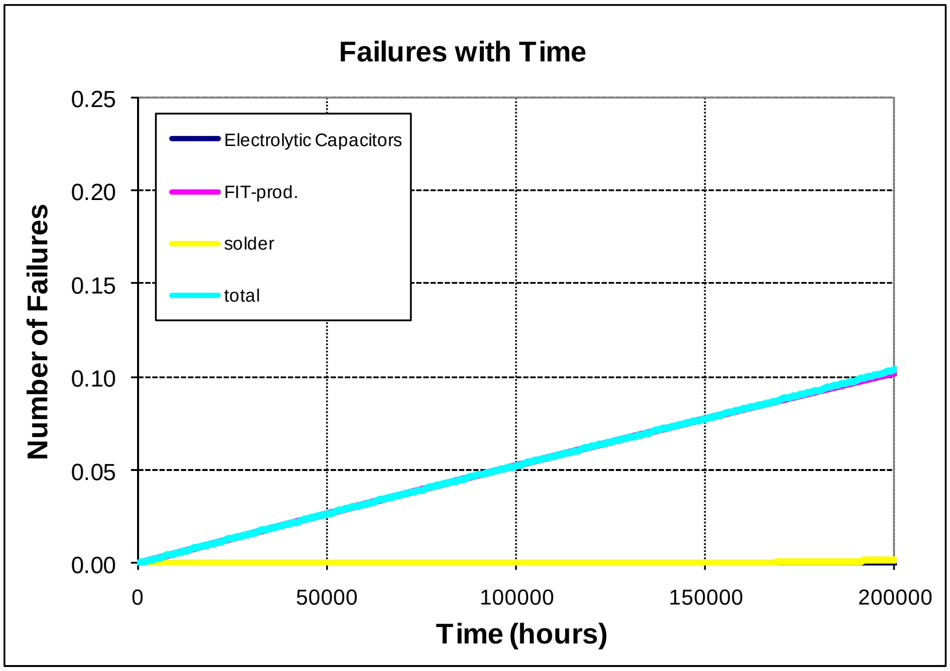

Figure 5

Please note that the data shown above is a theoretical calculation only and by no means can substitute for actual field data. Our experience has shown that this theoretical prediction is significantly higher than the actual field data. Therefore, whenever available, actual field return data should be used for predicting reliability.

Testing and Qualification: The issues identified above bring us to the next important step in the design process. Extensive qualification testing is performed at the design stage of the *Xitanium* drivers to ensure that any design issue is caught during the product development stage. The tests include operating the drivers at all possible operating conditions and also under conditions of extreme humidity and temperature. Accelerated life testing including HALT/ MEOST is also performed to ensure high driver reliability. Also, careful tests are conducted to ensure that all of the components operate within their maximum stress ratings (determined from the derating rules). Furthermore, compliance testing is conducted by various agencies to ensure that the drivers meet the relevant industry standards.

Another key factor in designing reliable products is to capture lessons learned from prior product field failure (which has been operating in the field and for which field failure data is available). This ensures that new products achieve improved levels of reliability compared to prior released products. Finally, during the manufacturing process, to prevent failures during infant mortality, a large sample of driver is subjected to an initial burn-in test. After the final assembly, a small sample of driver is operated at the maximum case temperature (HASS) for about 8 hours. Subsequently, the various critical parameters of the driver are measured. If there is any failure or significant shift in parameters of any driver in this testing then whole lot can be retested or re-worked or scrapped. The objective is to eliminate any manufacturing defects or component defect or wrong component etc.

Key Conclusions:

This document describes the strict design procedure followed for the development of *Xitanium* LED drivers to ensure high lifetime and reliability. The design and development of all *Xitanium* LED drivers pass through a tightly controlled process. The quality of product is critically evaluated at each milestone and activities to realize deliverables (and guidelines on how to perform such activities) are clearly defined. Besides all field return issues are carefully documented. All failure issues are reviewed at the start of each new project so that the leanings can be carried forward to new designs.

Further, the document also describes how the lifetime and reliability of the *Xitanium* LED drivers are evaluated. Model based on MIL-HDBK-217F reliability model is used to determine the theoretical failure rate of the drivers. Moreover, field return data obtained from previously released products show that the theoretical failure rates/MTTF results are significantly higher than actual field failure rate. Therefore, the theoretical MTTF data is meant to be an initial estimate and can give an idea regarding weak links in the design. It is however recommended that whenever possible, actual field return data should be used rather than calculated failure rate.

Concerned Part Numbers:

LEDINTA0024V41FOM /FLOM / DLOM

LEDINTA0350C425FOM / DOM

LEDINTA0700C21OFOM / DOM

LEDINTA0530C280DOM

LEDINTA700C14F3OM