EDN NETWORK

[As Strong as the Weakest Link: Reliability from the LED System Perspective]

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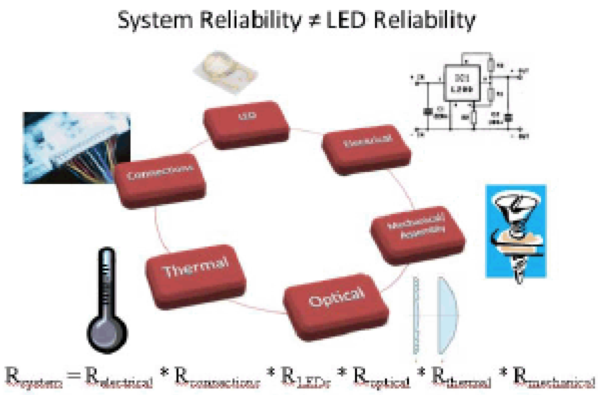
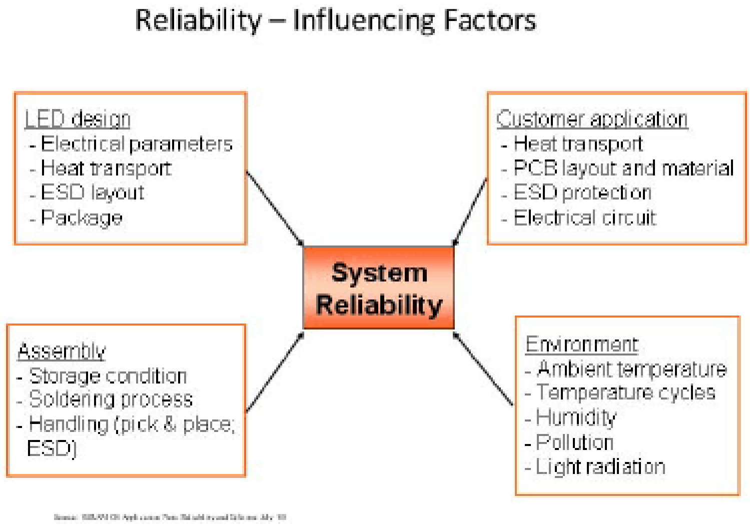
This paper, presented at DESIGN West, discusses the reliability of an LED System from a practical point of view. Models are provided for the long-term reliability and lumen maintenance behavior of the LED component. These models of single LED behavior are scaled to a system of multiple LEDs. Other aspects of LED system reliability are also discussed. Several best practices for manufacturing of the LED system are provided.



In a SSL system the reliability is determined by the weakest link. The LED manufacturer may understand the LED’s lumen maintenance and catastrophic failure behavior for the LED component, but the LED manufacturer has only limited control over the LED’s operating environment. In our experience the LED reliability is often not the limiting factor for the reliability of a SSL system, but rather the driver electronics and electrical connections. If the driver or electrical connections fail, the overall SSL system fails catastrophically. Other system components may have a degradation of performance over time. In fact a system analysis is complicated since each of the links has its own statistical failure distribution.



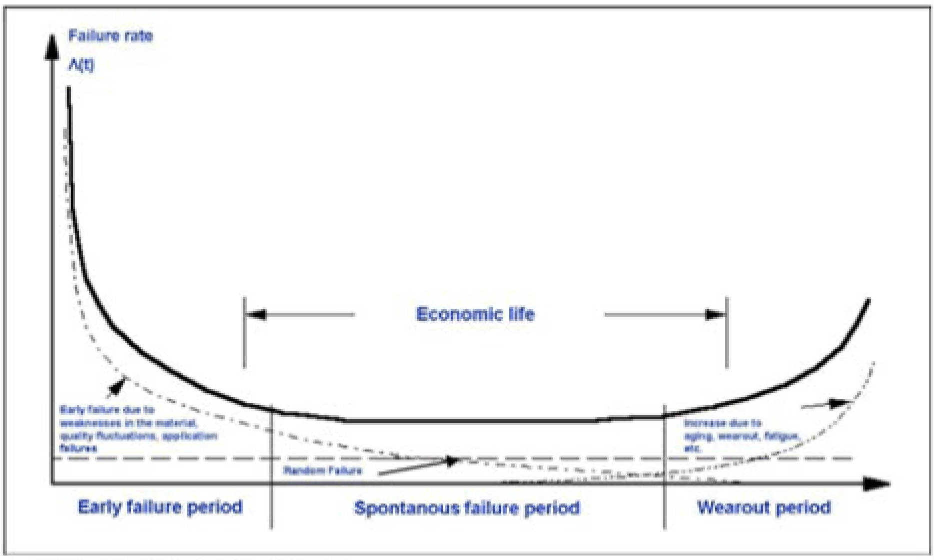
An LED SSL system is generally designed for long-term life in a certain operating environment. This environment includes the expected range in ambient temperatures, number of thermal and electrical cycles, range of humidity and moisture, possible exposure to sunlight (and UV radiation), and even environmental pollution.

The LED package design has a strong affect on the overall system reliability. Different packaging materials behave differently over temperature and over time. It is generally accepted that the failure rates of LEDs are related to junction temperature and drive current. Thus, the thermal path, junction to case, and the LED power dissipation directly affect the junction temperature. In addition, LEDs can be adversely affected by electrical transients, such as ESD or electrical spikes generated by the mains and electronic drivers.

The LED system design also directly affects the LED system reliability. Choices in materials used directly affect the thermal properties of the system. In addition, the choices of materials used directly affect the long-term behavior of the system with respect to environmental temperature cycling. The electrical driver design determines not only whether electrical spikes generated by the mains result in electrical transients applied to the LEDs, but also whether the on/off cycling of electrical drivers generate electrical transients being applied to the LEDs.

In addition, the manufacturing processes used for the assembly of the printed circuit boards (PCBs) and soldering process can have an impact on the long-term reliability of the LED SSL system.

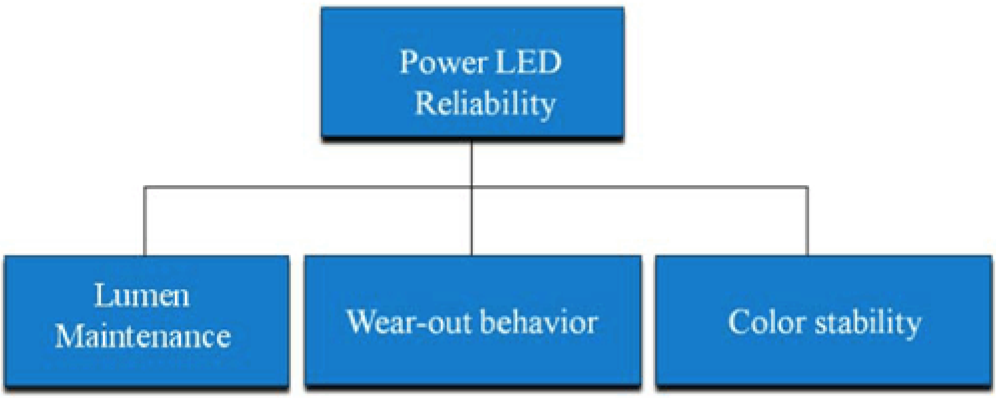
Chronological progression of system failure rate



Source: OSRAM OS Application Note Reliability and Lifetime July '08

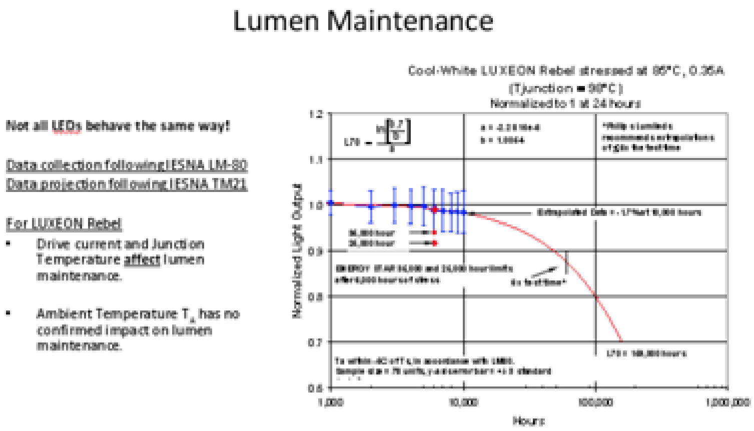
It is generally accepted in the electronics industry that the failure rates of an electronic component can be divided to be into three distinct regions – an early failure period, a random failure period, and a wear-out period.

LED Reliability



Today, we can develop separate reliability models for LED component lumen maintenance and for LED wear-out failures. In addition, the color stability of light generated by the LED is important for most LED SSL systems.

At the SSL system level, the impact of catastrophic versus lumen maintenance failures affects the SSL system differently. So it is better to keep the models separate. Lumen maintenance failures at the LED level, by definition, still mean that the SSL system lights up, only with some reduced light output. This may have only minimal impact on the other LEDs in the SSL system. Catastrophic failures, in contrast, generate no light, and may also impact the operation of other LEDs in the SSL system



The lumen maintenance graph above shows typical lumen maintenance behavior over time for a Cool-White LED at a specific drive condition. Note that this graph corresponds to 10,000 hours of actual lumen maintenance data. The heavy blue dots

show the average lumen maintenance behavior over time while the blue error bars show +/- 3 standard deviations for all LEDs tested.

The TM-21-11 method provides a means to extrapolate this lumen maintenance behavior beyond the actual tested time. The basic procedure is to normalize the average lumen maintenance data to 1 at 0 hours, and then to perform a least-squares fit of the last 5,000 hours of data to an exponential equation. The TM-21 committee was concerned about making very long-term lumen maintenance claims based on only a few thousand hours of tests, so the method puts a cap of 6X times the measurement time. 6X times 10,000 hours = 60,000 hours. So the heavy red line shows the 6X factor, and beyond this time, we show a light red line. As you can see from this graph, not all LEDs of a given type degrade at exactly the same rate. Thus the expected time to L70 is really a distribution of times.

The LM-80 test method requires lumen maintenance tests at multiple temperatures. Assuming that LEDs of a given type are also tested at multiple currents, then it is possible to generate a lumen maintenance model to predict time to L70 for a range of temperatures and currents. Under normal operating conditions, the probability of a LED catastrophic failure is very low. In order to generate a catastrophic failure rate model using only a few thousand hours of reliability testing, we need to stress LEDs at highly accelerated stress conditions, even higher than the maximum ratings. Because these tests are highly accelerated, it is also important to understand the failure mechanisms to ensure that the failures obtained in testing are typical of normal wear-out failures, and not different failure mechanisms caused by the extreme operating conditions.

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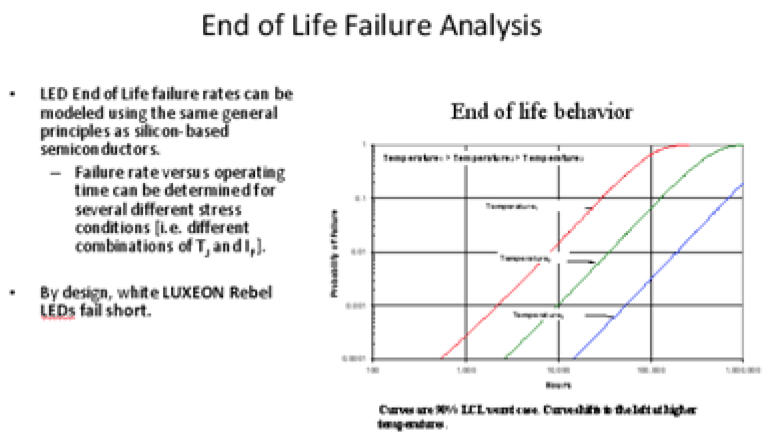
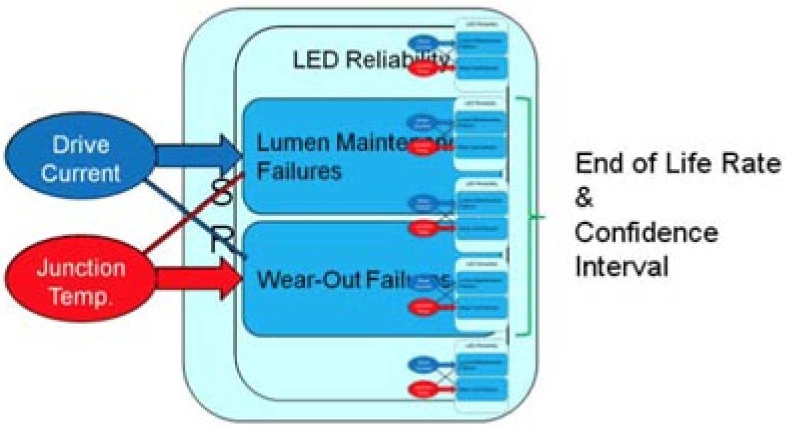
In practice, a catastrophic failure model can be generated by testing large samples of LEDs in several different operating temperatures and currents. Then the failure rate versus time at each stress condition (i.e. Tj and If) is fed into a standard reliability software package in order to develop a catastrophic failure rate model with temperature and forward current acceleration factors.

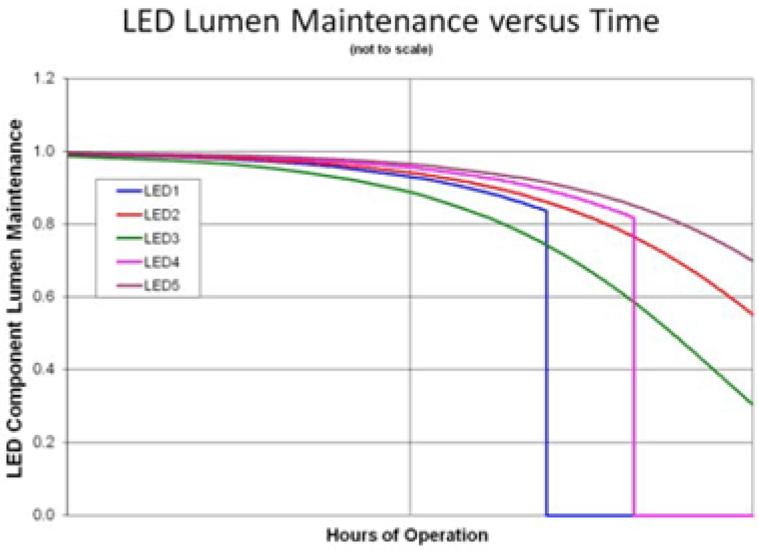
The resulting failure rate model is a Weibull reliability model. Now that we have a failure rate model, we can estimate the failure rates at any stress condition.

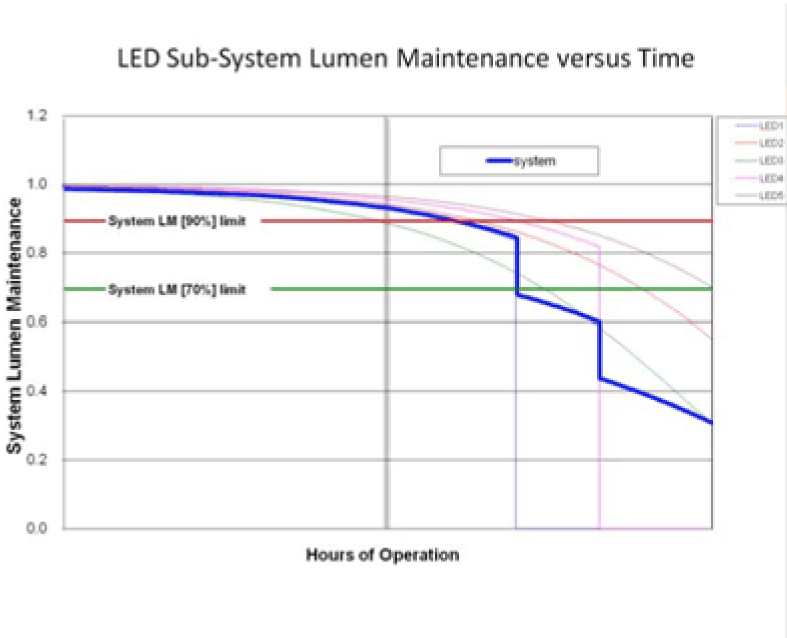


The graph above shows the impact of varying junction temperature on end-of-life failure rates. All three lines represent the worst-case 90% lower confidence limits. The blue line is the estimated wear-out failure rates driven at low junction temperature. The green line is the estimated failure rates at a 30°C higher junction temperature. The red line is the estimated failure rate at a 30°C still higher junction temperature. So the total temperature difference between the red and blue lines is 60°C. Note that the slopes of the graphs are the same and the impact of driving at a higher junction temperature is to cause the graph to shift towards the left.



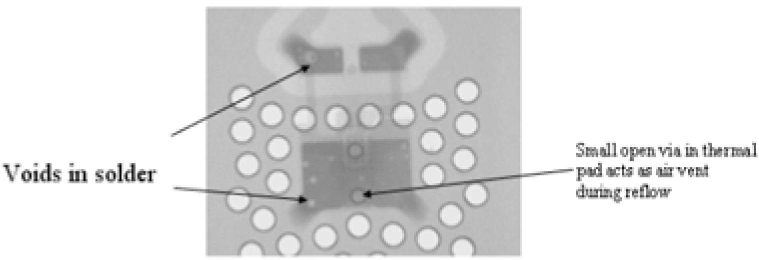
In an LED system, the impact of lumen maintenance behavior and wear-out behavior of each LED can be combined. In general, the wear-out failure behavior of the LED is an electrical short, where the LED generates no light, but current continues to flow through the LED. Thus, assuming that the LEDs are driven in a series-connected string with a current source, an electrical short in one LED ensures that all other LEDs in the system continue to operate at the desired forward current, but with a lower combined forward voltage across the series-string.





In terms of LED system light output, each LED gradually decreases with time. In the case of a wear-out failure, the light output of the LED which failed goes to zero abruptly. Thus, at the system level, the light output of the LED system drops slightly, depending on how many LEDs are used. At the system level, it is then possible to estimate the time for the system to fall below a desired light output.

Solder joint voiding criteria



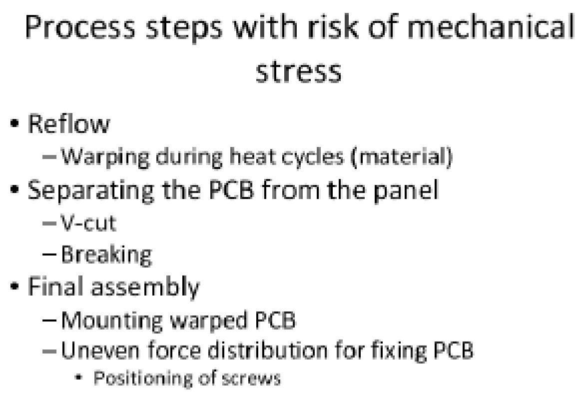
X ray image Rebel on FR4

IPC A-610d:

-8.2.14 Components with Bottom Thermal Plane Termination

Philips Lumileds recommendation: 26% voids max

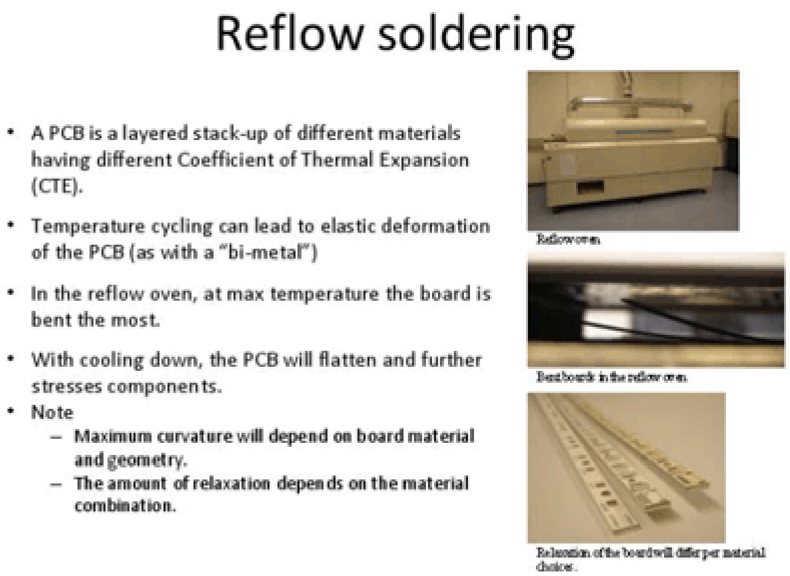
Solder voids can have an adverse impact on the overall LED system reliability. For many LEDs, the primary heat-flow path from the LED is though the solder connections. Solder voids can directly affect the thermal resistance of the LED, junction to air, potentially increasing the LED junction temperature during regular operation. In addition, solder voids can increase the possibility of solder cracking due to mechanical stresses applied to the PCB. However, as long as the percentage of solder voids is kept low, these possible effects are rather small.



Typical manufacturing processes can also cause mechanical stresses to be applied to the SMT components. For example, the solder reflow process can induce large thermal stresses in the PCB, resulting in a warped PCB. This, in turn, puts extra stress on the solder joints between the LEDs and the PCB.

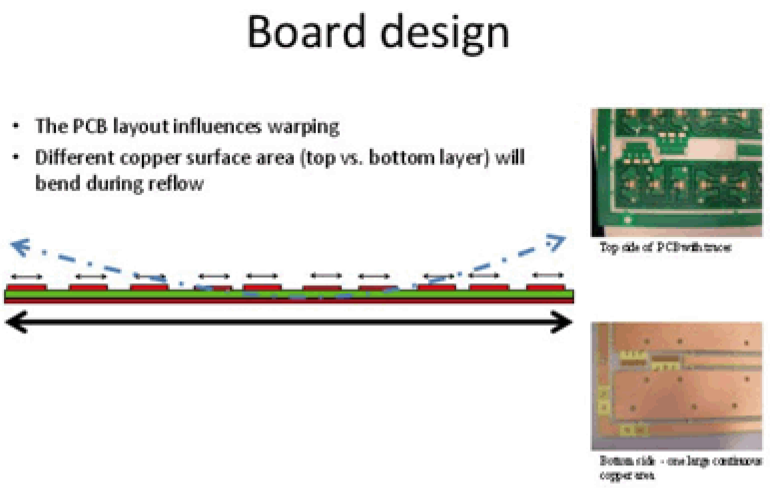
In addition, most PCBs are manufactured in a large panel. The components are placed on this panel and then reflow soldered in panel form. Without properly fixing the panel in place, removing the individual PCBs from the panel after soldering can put mechanical stress on the solder joints.

Finally, the assembly process itself may put mechanical stress on the solder joints. For example, if the PCB was bent during the solder reflow process, and the PCB is subsequently forced flat in final assembly, mechanical stresses may be induced in the solder joints between the PCB and the LEDs.



The photos above show a typical SMT reflow oven and several PCBs which were warped during the reflow process. Note that this problem is likely to be more severe when the PCB is a long thin strip as shown in these photos. Note that the mechanical stress is not an issue during the reflow soldering process itself.

However, it could become a problem later if the board is "flattened" down to make it conform to the desired flat shape in the final assembly. In addition, the number and positioning of the mounting screws can affect how much the PCB will flex during operation.



The soldering process applies a large thermal stress to the PCB. In the example pictures above, the FR4 PCB contains a solid copper layer on the bottom and only thin copper traces on the top side. Since the coefficient of thermal expansion (CTE) for FR4 is different than for copper, the PCB tends to warp during the reflow soldering process.

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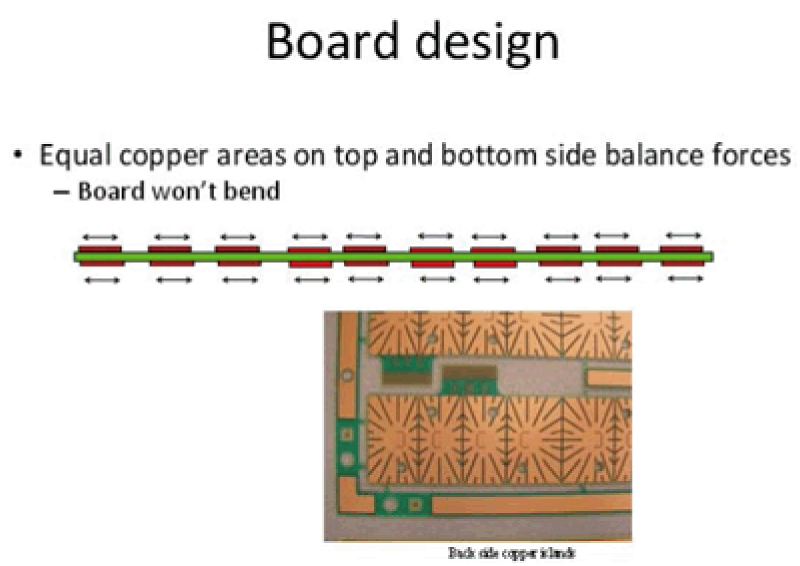
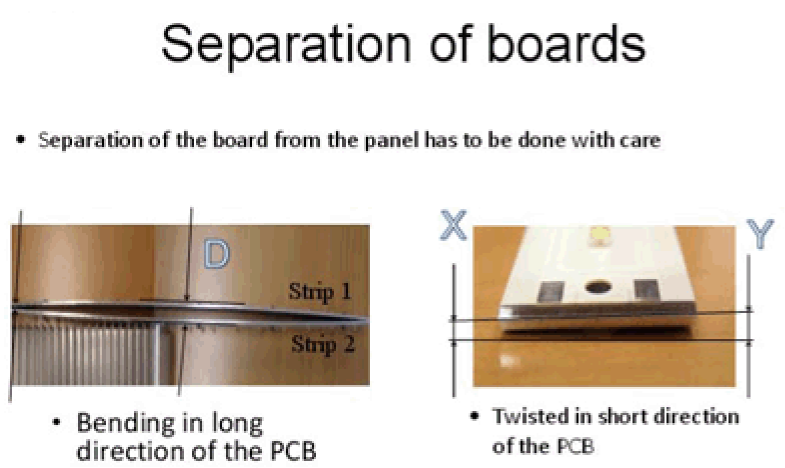
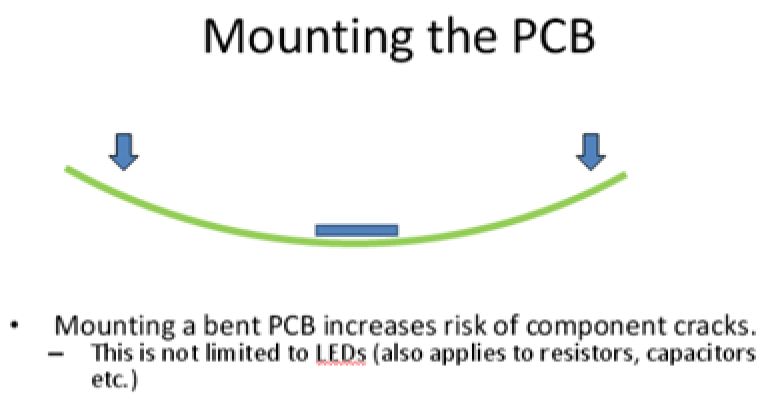


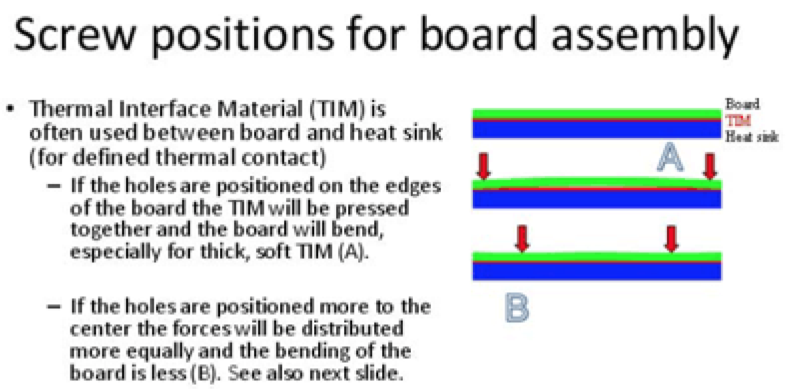
As shown in the picture above, this warping problem can be minimized by breaking the copper pad on the bottom of the PCB into smaller sections. Now the FR4 can expand without causing excessive warping. The bottom copper layer can be further segmented in order to further reduce mechanical stress during soldering



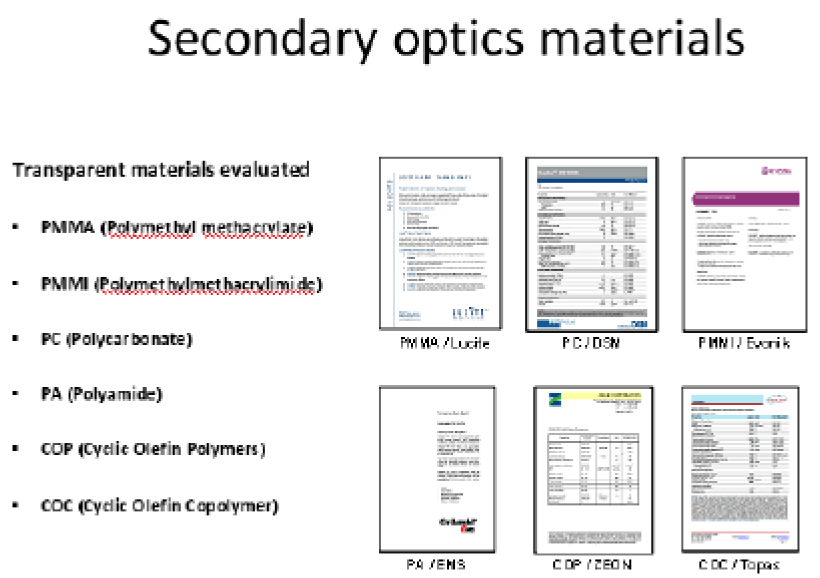
The photos above show another PCB design which was severely flexed during removal of the individual boards from the panel. This bending was eliminated by securing the PCB panel in place before he individual PCB boards were separated from the panel.



The picture above shows a highly exaggerated view of a ceramic-based component mounted on PCB, where the PCB is being flexed. Many electronic components including chip resistors, chip capacitors, and many LEDs, use ceramic substrates. Since ceramic is brittle, a large mechanical stress like this could easily crack the ceramic material. In addition, the solder joints are also likely to be damaged by this type of mechanical stress

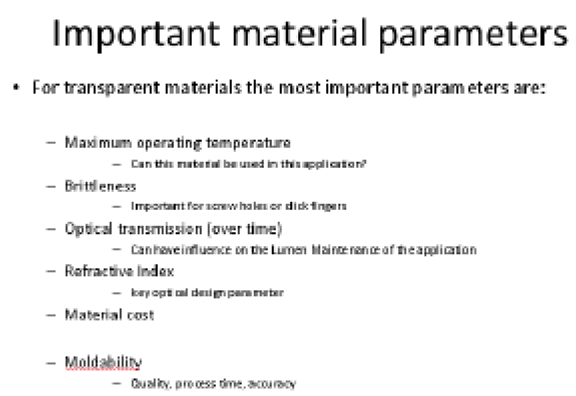


Some PCBs can flex due to the mechanical spacing between the mounting screws and the compression of the thermal interface material between the PCB and the heatsink.

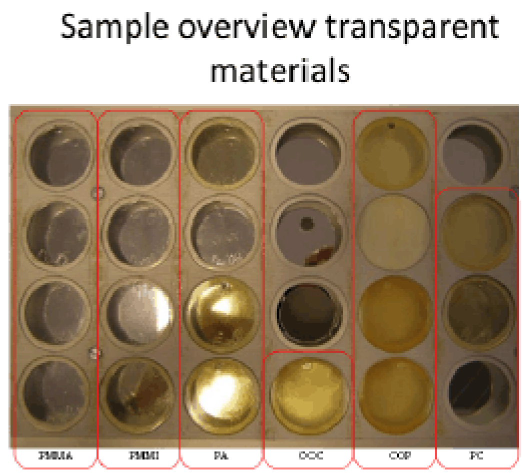


There are many choices for the secondary optics materials. Each material has different mechanical properties. With respect to long-term reliability of the LED system, it is important to understand whether the optical transmission of the secondary optics will change over time. If the optical transmission degrades with time, then the SSL system will experience light degradation.

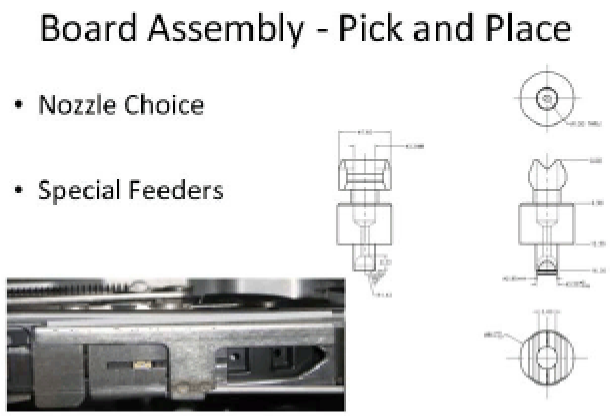
In many SSL applications, the LED system will be mounted in an outdoor environment, so UV from the sunlight may adversely affect the secondary optics. In addition, while InGaN LEDs do not generate UV light, the blue light generated by a typical white LED can also potentially damage the plastic materials due to exposure over long periods of time. If a plastic material can survive long-term UV exposure, then it generally also survive exposure to blue light. Conversely, if plastic materials are damaged by UV exposure, then they may also be affected by exposure to blue light.



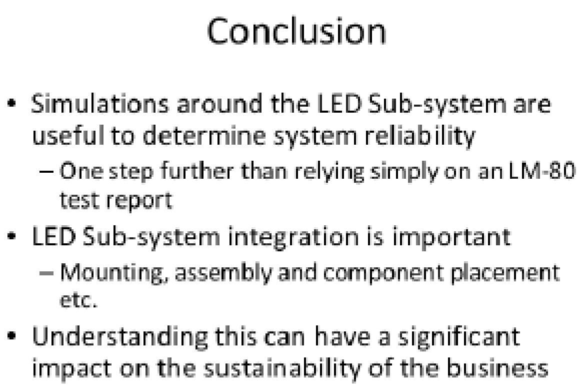
This slide lists some of the key properties of plastics materials designed for secondary optics.



This slide shows how the materials look after long-term UV exposure. The best materials are still water-clear. Some materials have yellowed. The worst materials have also turned translucent.



The design of the pick-and-place nozzle is important to ensure that the LED package is not damaged in handling. In addition, the design of the nozzle may affect the positioning accuracy of the components on the PCB.



The long-term reliability of an LED system can be determined by combining the lumen maintenance and wear-out reliability models for the LEDs with the reliability wear-out behavior and lumen maintenance behavior for the other key parts of the LED system. One way that this can be done is through the use of Monte-Carlo simulations where random selections of components are combined together into a combined system, and the system ‘life-time’ can be determined. Then the results of multiple Monte-Carlo simulations can be combined together into a distribution of system behavior.

Manufacturers generally provide warranties for their LED systems. While it may not be practical to perform reliability testing of LED systems for 50,000 hours, it is very possible to model the reliability behavior of the LED system. This reliability modeling is important in order to estimate the business costs associated with this warranty.