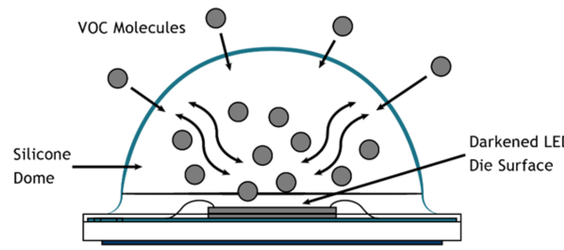
Guidelines to Prevent LED Damage Due to Contamination



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Introduction

Contaminants can darken LEDs, resulting in rapid light output degradation. This effect can be amplified when exposure to environmental pollutants is combined with high temperatures and/or high intensities of high-energy photons in an environment with little to no ventilation. When contamination occurs, it darkens the die surface, blocks the light, and thus dramatically depreciates the LED's luminous flux.

Some materials may be more likely to cause LED darkening under specific conditions. Contaminants can also damage LEDs through corrosion, causing open circuits. The silicone encapsulant can be damaged due to swelling, bulk discoloration, and loss of adhesion.

This Application Note describes the various contaminants and their effects on LEDs. It also provides design guidelines to prevent LED darkening when using high-power LEDs.

1. Introduction

Multiple factors can affect LED performance, reliability, and lifespan. Design engineers and those working with LED components must take these factors into account. The causes of LED performance degradation can be categorized into three types of stressors: electrical, thermal, and contamination stress (Figure 1).

To fully benefit from Luminus LEDs' high-performance functionality, contamination prevention, power supply design, and thermal management should all be carefully considered in luminaire design. To succeed in designing LED systems, these components must be considered using best practices. Otherwise, LED performance will be hindered, and failure or other permanent damage may occur.

This Application Note addresses contamination stress factors and prevention practices with a focus on Luminus light emitting diodes (LEDs). LED devices are particularly sensitive to contamination damage. Contaminated devices can appear dim, develop an open circuit, or become shunted.

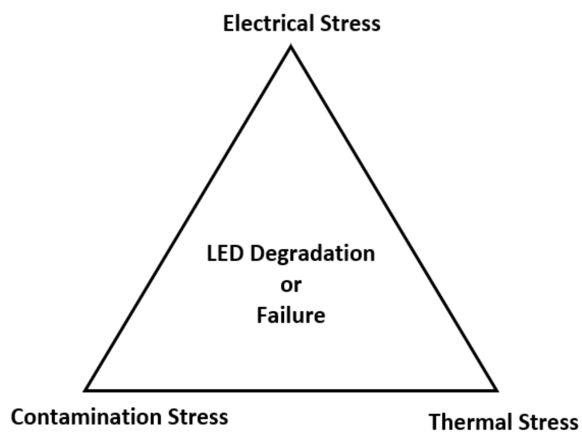

Figure 1. Stressors that cause LED performance degradation or failure.

It is important to understand the circumstances that cause contamination, as it is often catastrophic for LEDs. The most common drivers of LED darkening are:

- Exposure to Volatile Organic Compound (VOC) contaminants
- Exposure to Sulfur-containing contaminants
- Poor ventilation practices in fixture design
- High system operating temperatures
- Excessive voids in the soldering joints leading to higher than expected LED temperatures.

These contamination sources and methods to avoid or mitigate each of them are covered in this Application Note. For information and prevention guidelines for the other two primary stress factors, electrical stress and thermal stress, refer to the References and Resources section of this document.

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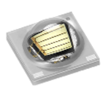
1.1. LED Package and Luminaire Components

Luminus manufactures multiple types of LEDs, listed in Table 1 and shown in Figure 2.

Table 1. Luminus LED Products.

LED Type	Typical Power	Function and Applications
High-Power LED 	1 to 5 Watts	Designed for high-reliability applications and designs that require small optical source sizes with high luminous flux
Mid-Power LED 	0.1 to 10 Watts	Designed for applications requiring multiple light sources and diffused emission
Chip-on-Board LED (COB) 	2 – 300 Watts	Designed for lighting applications that require high luminous flux from a small optical source or extremely high luminous flux density
Chip Scale Package (CSP) 	0.5 – 1 Watt	Designed for applications that require a compact LED. Lower cost alternative to high- and mid-power LEDs.
Core Board LED 	50 – 100+ Watts	Designed for applications that require an extremely high flux from a small area. Projection systems and fiber-coupling are examples.

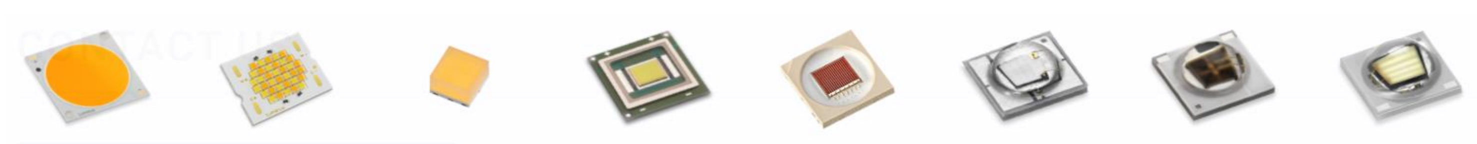


Figure 2. Luminus LED product lines include high- and mid-powered LEDs, COB, UV and IR, and more (not all images are shown to scale).

Functionally, all of these LED package designs have the following elements:

- LED chip – a semiconductor device that is the source of light and heat. Luminus LED chips have a wide range of wavelengths from the ultra-violet (UV) to near-infrared (NIR).
- Substrate – holds the chip securely in place and provides electrical connection points. Provides an efficient thermal path downwards towards the system heatsink.
- Phosphor element (optional) – converts a fraction of blue LED emission to longer wavelengths, tuned to produce white, green, and red broadband light sources.
- Encapsulation element – a transparent material applied to the top of the LED chip to enhance and control light output.

These LED packages are incorporated in LED luminaire systems, which contain a wide variety of materials that can potentially be a source of contamination. The materials must not contain large amounts of known deleterious compounds; these are listed in the Appendix, in Table 5. The geometry of the luminaire must not trap contaminants near the LEDs. If LEDs are allowed to “breathe”, small amounts of contaminants can be tolerated [1]. Figure 3 shows elements of a typical LED system. Both the geometry of the luminaire design and the construction materials need to be considered to eliminate the possibility of contamination-related degradation.

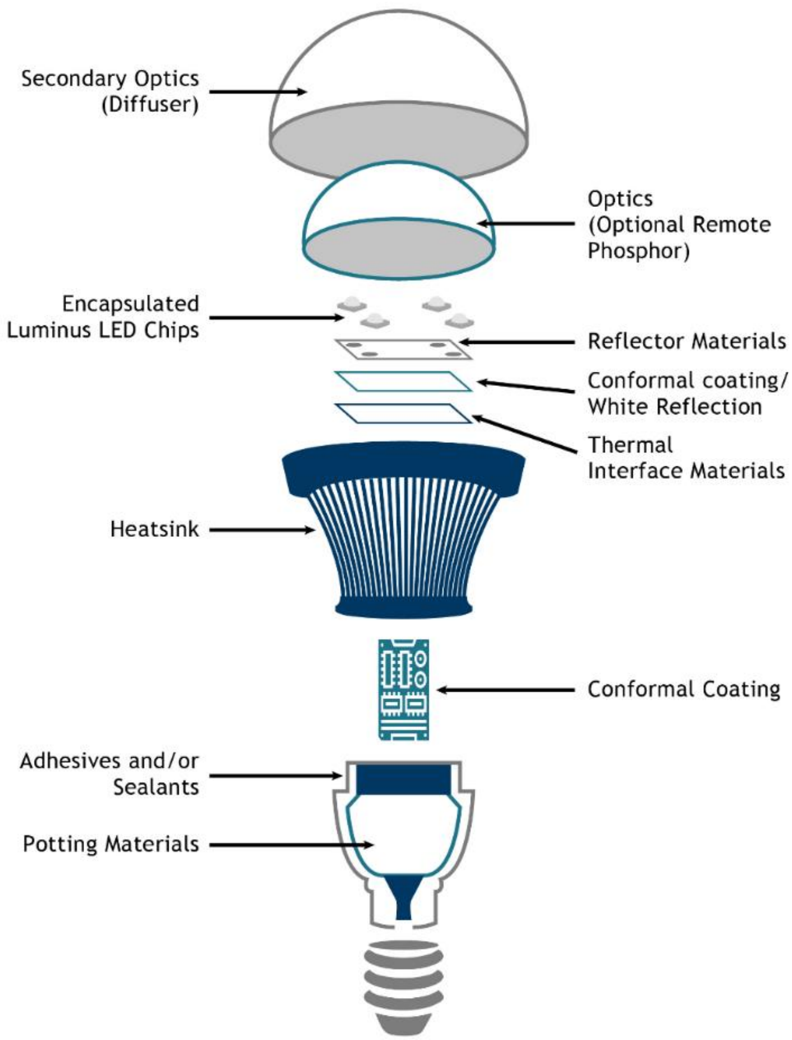


Figure 3. A typical luminaire design showing many of the multiple components that must be assembled properly to ensure safety and performance.

2. LED Darkening Mechanisms

Common contamination-driven mechanisms of LED dimming are:

- Volatile Organic Compound (VOC) contamination
- Sulfur metallization corrosion
- Carbonization of contaminants on the silicone dome encapsulation
- Moisture penetration
- Silicone swelling
- Excessive voids in the soldering joints, which can exacerbate the effect of contaminants and can cause carbonization.

The following sections will delve into each of these issues and discuss the most common issues luminaire designers face. Additional causes of LED darkening are addressed in Appendix A:

- Metallization darkening
- Silicone darkening
- Silicone delamination
- Material staining.

2.1. Volatile Organic Compound (VOC) Induced Darkening

LED darkening occurs when VOC molecules diffuse to, or near, the LED surface and are subject to bond breaking due to some combination of heat, photonic energy, and/or light intensity. LED darkening dramatically decreases luminous flux output, negatively impacting expected LED performance. Therefore, it is necessary to understand the mechanisms that can result in VOC-driven LED darkening. The primary mechanisms in VOC-driven LED darkening are:

- **Temperature** – LED chips can get very hot while in use, especially when overpowered. Increased chip temperature promotes breaking of VOC chemical bonds.
- **LED Wavelength (Photon Energy)** – The photon energy of emitted light correlated with the occurrence of VOC darkening. The threshold for this effect is in the green wavelength region. Blue light generally contributes to VOC darkening. Red light typically does not. Green light can contribute to VOC darkening at high flux levels.
- **Light Intensity (Luminous Intensity)** – The light intensity also contributes to VOC darkening. The light flux at the surface of an LED under normal conditions is very high so this driver is always present.
- **VOC Concentration** – High concentrations of VOCs will result in more severe darkening. The threshold levels are not well established. System designs that trap VOCs exacerbate the effect.

VOC-induced LED darkening results in discoloration, causing the LED surface to take on a yellow or brown color, as shown by the examples in Figure 4. Darkening can dramatically depreciate the luminous flux performance of the LED, causing it to emit significantly less light. With white LEDs, the color point can be shifted due to VOC darkening.

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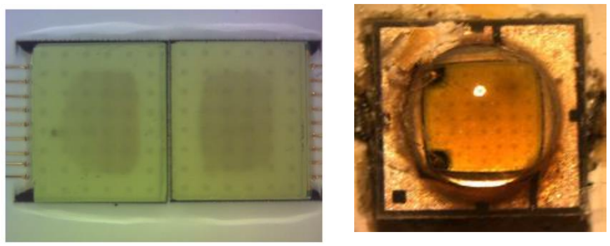

Figure 4. Examples of VOC darkening.

VOCs outgas (are released as gas/vapor) from many materials such as solvents, adhesives, polymers, and a variety of organic chemical compounds. VOCs may be emitted by system components near the LED or from materials stored near the assembly processing location. Deployed LED systems can also be exposed to environmental pollutants containing VOCs. Refer to Table 5 in the Appendix for a list of common chemical compounds to avoid in luminaire design to prevent VOC-driven LED darkening.

Virtually all LED packages use an optical grade silicone as the encapsulating material. Silicone has an open pore structure and has essentially no diffusion barrier properties. VOC gas molecules diffuse through the permeable silicone dome and come in contact with the LED chip surface. The high heat and photonic energy generated during LED operation causes VOC darkening near the chip surface. Figure 5 illustrates the VOC molecules diffusing through the silicone dome and highlights the location of the die.

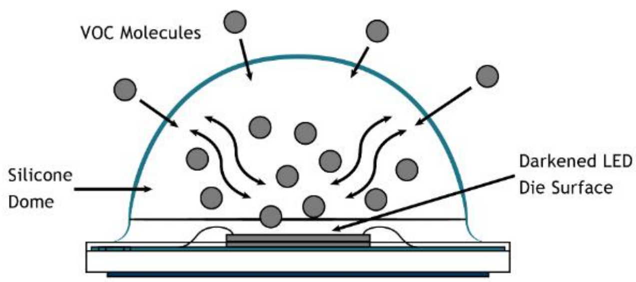

Figure 5. VOC molecules diffuse through an LED's silicone dome encapsulation.

VOC-induced darkening is often reversible. The silicone dome and LED chip are generally not affected by VOC contamination and contaminants can be driven out of the package by using a burn-in process. In an open area with adequate ventilation, VOC-driven LED darkening will likely not be severe and will dissipate quickly. Consult with Luminus support for product-specific burn-in requirements and procedures.

Figure 6 shows an example of a Luminus LED's lumen output measured during a burn-in process. The measured lumen output drops within the first hours before recovering to full lumen output. There is no permanent effect on LED performance once the VOC contaminants have dissipated.

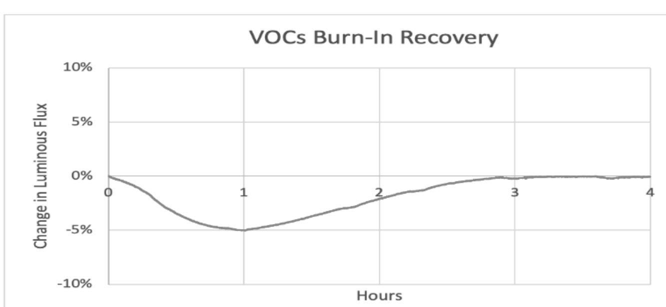

Figure 6. Lumen output of a Luminus LED is fully recovered (by the end of hour 3) following the burn-in period (hours 1-3).

2.2. Sulfur Metallization Corrosion

Sulfur is a common element that reacts with the metallic materials used in LED construction such as silver and copper. Sulfur can evaporate from paper, drywall, or the cardboard often used in electronics transportation. Other materials such as foam, rubber sealant, elastomers vulcanized with sulfur, thermal conductive pads, and anti-vibration pads can release sulfur. Sulfur can also be found in some types of oils and lubricants, rubber gaskets, hoses, belts, grommets, and connectors. It is often a low-level air pollutant due to nearby automotive combustion.

Silver is used in LED designs to enhance reflection in the device. When sulfur permeates through the silicone dome and corrodes the silver, this corrosion darkens the reflection of the silver and reduces the luminous output of the LED (Figure 7). Sulfur corrosion of the underlying copper traces in an LED package can cause open circuits.

Increased humidity levels or heat will enhance the reaction and thus increase the formation rate and amount of metal-sulfur intermetallics. The presence of low levels of sulfur during the reflow process has been known to degrade LED lifetimes. To prevent silver sulfide or copper sulfide from forming, it is essential that the luminaire designer ensure no sources of sulfur exist near the LED. Luminus recommends the use of sulfur detectors in the manufacturing environment and training personnel how to identify and eliminate common sulfur sources such as cardboard and solvents.

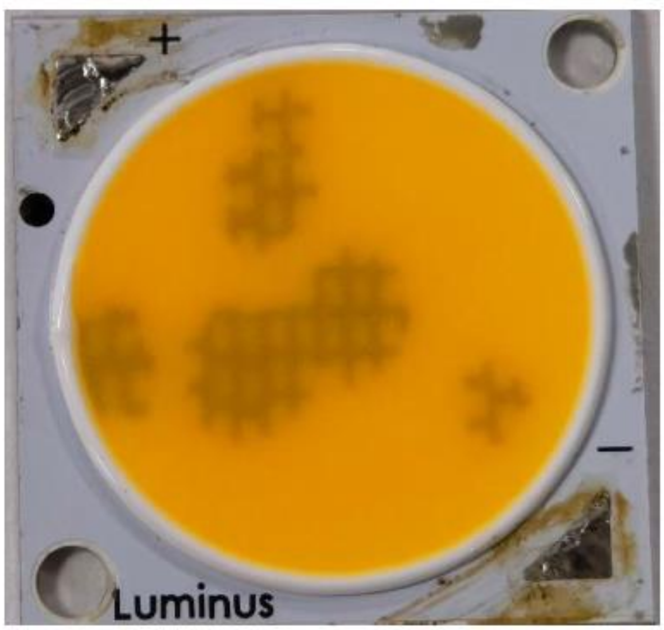

Figure 7 – Example of silver-plated substrate darkening due to storage in an area with an excessive level of sulfur-containing compounds.

In the field, we have observed the most common sulfur corrosion problems arise:

1. When parts are removed from the barrier bags they are shipped in and then stored in a warehouse or other unprotected environment. Warehouse spaces have many sulfur sources, principally cardboard and rubbers, and LEDs need to be isolated within barrier bags or nitrogen boxes.

2. From overspray contamination of unprotected LEDs from sulfur-containing compounds in horticulture installations. For horticulture applications where sulfur is required to promote yield, consult with Luminus to identify parts with better resistance and on luminaire design to minimize direct exposure.

2.3. Carbonization on the Silicone Encapsulation Surface

A silicone dome is often used to encapsulate the LED, providing protection, optical enhancement, and thermal management to the LED. Because LEDs run at high temperatures (especially when overpowered), the silicone dome encapsulation can get hot enough to carbonize VOC molecules and other physical contaminants that come in contact with the silicone dome, as shown in Figure 8. This carbon remains on the silicone dome as a black mark. As the contaminants are heated further and more contaminants are carbonized, the black marks grow to cover the dome and significantly affect the light output.

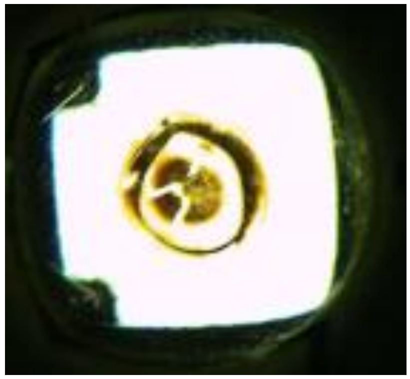

Figure 8 - Silicone Dome with Carbonized Contaminants

The most common cause of this mechanism is physical contamination combined with excessive temperature. If a small seed droplet of foreign material is deposited on the encapsulation material, it heats up drastically due to light absorption and starts to convert low level VOCs and grow. Extreme VOC concentrations can also cause this problem. It is often associated with excessive solder joint voids where the LED temperature is much higher than intended.

2.4. Moisture Penetration

Silicone is permeable to moisture and at severe humidity levels can suffer permanent damage due to moisture effects. Generally, moisture absorption into the silicone dome occurs when the LED is powered off in high-humidity locations. The silicone is porous, and the moisture will saturate the silicone dome while the LED is off and cool. After moisture vapor has saturated the silicone dome, the LED is powered on, and the significant temperature increase will drive the moisture vapor to expand. The moisture vapor expands inside small voids within the silicone material, causing and growing microcracks in the encapsulation. If these hydro-mechanical stresses crack the silicone dome, the LED light output is significantly reduced, and the color point of the device can be changed.

Provided you follow appropriate thermal management practices, and the LED is not overpowered beyond the maximum operating temperature defined in the product's data sheet, this is a minor effect that is evaluated during LED design qualification and can be predicted using reliability reports (provided on request).

2.5. Silicone Swelling

The performance characteristics of silicone rubber and silicone/phosphor composites can be affected by exposure to or immersion in certain fluids. For example, it will swell due to moisture absorption, causing the silicone to fall off, affecting the beam pattern and possibly darkening the LED. For a list of common chemicals that cause silicone swelling, refer to Table 5 in the Appendix. Additionally, Dow Chemical Company provides an extensive list of silicone swelling and tensile strength changes due to exposure to various chemicals; refer to citation [2].

2.6. Excessive Voids in the Solder Joints

Voids in the solder joints of the LED are not a type of contamination, per se, however they are a significant contributing factor in contamination degradation rates, thus are important to include here. Voids may result from manufacturing processes. They can easily be characterized using X-ray imaging. Luminus recommends performing X-ray inspection during reflow process development with an acceptance criterion for solder joint quality as Cpk > 1.25 (or 1.60) for void count percentage using a 20% single-sided limit. Establishing an SPC sampling plan for X-ray inspection during mass production is recommended. Figure 9 shows comparative x-rays of an LED with excessive voids in the soldering joints (appearing as light spots) and an LED with an acceptable void count in the soldering joints.

Figure 9, Comparison of good and bad void levels in a solder joint.

Excessive voids in the soldering joints will reduce the thermal conductivity of the device, resulting in poor thermal management at a fundamental level. Because of this poor thermal management within the device itself, the p-n junction (along with other components of the device) can overheat well past the maximum operating temperatures. This overheating will affect not only life span of the LED, but also reliability, performance, and light output.

To learn more about how to prevent excessive voids in the soldering joints and other vital thermal management considerations, consult Luminus Help Center article "How do I Reflow Solder Luminus SMD Components?"

3. Controlling Driving Mechanisms: LED Darkening Prevention

LED darkening can be reduced or prevented by addressing any of the driving mechanisms outlined above. System-level luminaire design considerations that will help prevent LED darkening include:

- Check potential material compatibility with Luminus LEDs by referring to the Appendix
- Test all materials and LEDs in the specific application, environment, and conditions in which they are intended to be used
- High temperatures that exceed operating limits will facilitate LED darkening
- Design with ventilation in mind.

No matter what the application, ventilation is critical to both preventing and remedying LED darkening. Ventilation precludes contaminant accumulation, thereby reducing the likelihood of reaction with a device. Contaminant dilution through ventilation is necessary to maintain high luminous flux output.

Rather than air-tight housing, Luminus recommends using ventilated enclosures. For example, membranes designed specifically for LED housing applications will allow air to flow through the system but will prevent any water or other particulates (such as dust) from penetrating the electronics. The objective is to allow the LED plenty of ventilation while still protecting it from contaminants. Creating an air-tight system, no matter the intended positive benefit, is strongly discouraged.

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Without proper ventilation, LEDs will have little chance of avoiding or recovering from LED darkening. Luminus strongly recommends that you:

- Provide enough room between the LED and the lens.
- Do not seal the LED completely into an air-tight system.
- Ensure air can flow around the interface between the LED and the lens, which will provide better ventilation and help prevent LED darkening.
- Design any lens holders to allow for ventilation and air circulation.

4. Conclusions

Contamination prevention is one of three vital considerations for effective LED luminaire design, along with issues of thermal and electrical stress. Contamination with VOCs can cause LED darkening, resulting in rapid light output degradation and dramatic reduction of the LED's luminous flux. For example, certain chemical substances, moisture, and soldering issues can all impact LED performance.

To prevent darkening due to VOC contamination, designers must select compatible materials for luminaire construction. Additionally, they must address thermal management and proper ventilation to ensure high performance and longevity of the device.

High performance, efficient functionality, and reliability can be achieved when power supply, contamination prevention, and thermal management are all considered in LED luminaire system design.

5. References and Resources

Luminus Resources

Refer to the Application Notes related to LED performance degradation, found in the Resources section of the Luminus website. Refer also to the Luminus online Help Center/FAQ, which contains detailed information on multiple topics related to LED performance, handling, testing, incorporation into luminaires, and more.

Additional Resources

The following resources provide additional information about VOC contamination of LEDs:

- Jellesen, M.S., Verdingovas, V., et al., “Sulphur induced corrosion of electronics”, Materials and Surface Engineering, Department of Mechanical Engineering, Technical University of Denmark. Conference proceedings. Link to PDF.
- Mehr, M.Y., Bahrami, A., et al., "Degradation of optical materials in solid-state lighting systems," *International Materials Review*, 2020 65(2): 102-128. doi.org/10.1080/09506608.2019.1565716
- Sciascia, C., Corazza, A., et al., “Effective Solution to Prevent Degradation of LED Systems Due to Sulphur and Chlorine Compounds”, *Journal of Science and Technology in Lighting*, September 2017. DOI: 10.2150/jstl.IEIJ170000612
- Singh, P., and Tan, C. M., “Degradation Physics of High-Power LEDs in Outdoor Environment and the Role of Phosphor in the degradation process”, *Scientific Reports*, April 2016, Vol. 6, article no. 24052. LINK

Citations

[1] Mehr, M.Y., Bahrami, A., et al., "Degradation of optical materials in solid-state lighting systems," *International Materials Review,* 2020 65(2): 102-128. doi.org/10.1080/09506608.2019.1565716
[2] *Performance profiles for SILASTIC™ Silicone and Fluorosilicone Rubber and XIAMETER™ Silicone Rubber*: *Fluid resistance guide*. Dow Chemical Company, 2019. LINK

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Appendix

Table 5 lists the compatibility of common chemical compounds with LEDs. This table is intended to help guide the design surrounding the LEDs, however Luminus highly recommends that all materials and LEDs be tested in the specific application, environment, and conditions in which they are intended to be used. This list does not guarantee LED darkening will be prevented entirely. This list is provided for informational purposes only and is not a warranty or endorsement.

Note: There are many conformal coatings that are acceptable in proximity to LEDs, however, using conformal coatings on LED domes can result in reliability issues.

Note: Isopropyl alcohol (IPA) and deionized water (DI) are the recommended cleaning solutions for Luminus products.

Note: The concentration levels that result in degradation are not easily quantified. Evaluation of luminaire designs is generally required.

Table 5 – Contaminants to be Avoided in LED Design

Failure Mode	Where Commonly Found	Contaminants
Material Staining (surface of the package, metallization inside the dome)	Adhesives, cleaning solutions, coatings, elastomers, epoxy, sealants	Diamine, petroleum products (all), phenyl mercuric neo-decanoate, polynorbornene rubber, polystyrene, potassium hydroxide, residual activated solder flux, rubber, tetrachloromethane, tetradecyl amine, trimethyl-hexamethylene, uncured polyurethane, sulfur-containing compounds
Metallization Corrosion	Adhesives, car exhaust, cleaning solutions, cutting fluids, degreasers, flame retardants, plastics, RTV silicones, rubbers, sealants, solder paste (flux residue), solvents, uncured conformal coatings	Acetic acid, acrylates (all types), chlorine-containing compounds, epichlorohydrin, halogenated hydrocarbons, hydrochloric acid, methyl or ethyl acetates, nitric acid, petroleum products (all), rubber, silicone rubber (acetic-acid-curing), sulfur-containing compounds
Moisture Penetration	Ambient humidity	H_2O vapor
Silicone Carbonization	Occurs only with high temperature at the surface of the silicone dome. At high temperatures, any hydrocarbon present can seed on the dome and grow rapidly due to accelerated light absorption heating	Contaminant list is the same as "VOC Contamination and Silicone Carbonization" (below)
Silicone Delamination	Adhesives, coatings, elastomers, machining operations, sealants	Cutting fluids, petroleum products (all), phenyl mercuric neo-decanoate, release agents, rubber
Silicone Discoloration (bulk effect)	Adhesives, cleaning solutions, rubbers, structural plastics, uncured conformal coating	Aldehydes, amines, ammonia, butadiene rubber, cyanoacrylates, dichloromethane, dienes, neodecanoic acid glycidyl ester, nitric acid, petroleum products (all), rubber
Silicone Swelling **Refer to List of swelling and tensile strength changes [2]**	Cleaning Solutions, solvents	Acetone, bleach, chlorine compounds, formaldehyde, glycol ethers, methyl ethyl ketone (MEK), petroleum products (all), phenyl-mercuric neo-decanoate, formaldehyde, glycol ethers, rubber

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Failure Mode	Where Commonly Found	Contaminants
Sulfur Metallization Corrosion (of silver/copper elements in the LED)	Paper, drywall, cardboard, foam, rubber sealant, elastomers vulcanized with sulfur, thermal conductive pads, anti-vibration pads, some oils and lubricants, rubber gaskets, hoses, belts, grommets, connectors, automotive exhaust, cutting fluids, fertilizers, mineral spirits, paints, paper, petroleum oil, rubber bands, rubbers, sealants, pesticides	Hydrogen sulfide, rubber, petroleum products (all), sodium sulfide, sulfur containing compounds, sulfur dioxide, sulfuric acid, sulphuryl chloride
VOC Contamination and Silicone Carbonization	Many materials such as solvents, adhesives, polymers, organic chemical compounds, thread lock fluids	Acetic acid, acetone, acrylates (all types), ammonia, ammonium sulfide, aniline, benzene, bleach, bromine, butadiene rubber, butyl rubber, camphor oil, carbolic acid, carbon disulfide, carbon tetrachloride, chlorine-containing compounds, chlorobutyl rubber, chlorosulphonated polyethylene, cutting fluids, cyanoacrylates, cyclo hexane, diamyl phthalate, dichloromethane, dipropylene glycol monomethyl ether, epichlorohydrin, ethyl acetate, ethyl amine, ethyl bromide, ethylene chlorohydrin, formaldehyde, glycol ethers, halogenated hydrocarbons, hydrochloric acid, hydrofluoric acid, hydrogen peroxide, iodine, isoamyl alcohol, many types of inks (especially Sharpie® pens), Kapton tape with acrylic-based adhesives (silicone-based adhesives are OK), methacrylic acid-methyl ester (MMA), methanol, methyl amine, methyl ethyl ketone (MEK), methyl isobutyl ketone, methyl or ethyl acetates, methylene chloride, nitric acid, pesticides, petroleum products (all), phenols, polymer plasticizers, potassium hydroxide, rubber, silicone oil, silicone rubber (acetic acid curing), sodium hydroxide, sodium sulfide, sulfur-containing compounds, sulfuric acid, sulfur dioxide, sulphuryl chloride, toluene, trimethyl hexamethylene diamine, xylene