Application Note

Disinfection with UV-C LEDs

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1 Introduction

This application note gives you an overview how disinfection with UV-C light works, the benefits of UV-C LEDs and safety issues that need to be considered when using UV-C LEDs in applications.

Due to the recent COVID-19 pandemic the need for disinfection technologies has skyrocketed. One of these technologies is disinfection using UV-C LEDs. Ultraviolet (UV) light radiation is more energetic than visible light. It is classified by its wavelength into three subgroups:

- **UV-A** (315-400 nm)
  Mainly used for material curing applications and horticulture
  WL-SUMW
- **UV-B** (280-315 nm)
  Mainly used for phototherapy and horticulture
- **UV-C** (100-280 nm)
  Used for disinfection purposes WL-SUMW

The disinfection capability of UV light has been known since 1877 [1] and already gained great interest in the fight against diseases such as preventing the spread of tuberculosis [4, 5]. In the past, low-pressure mercury-vapor discharge lamps were used for disinfection as they emit at the germicidal wavelength of 254 nm and have relatively large radiant powers. To date, they are often the most economic solution for large scale disinfection.

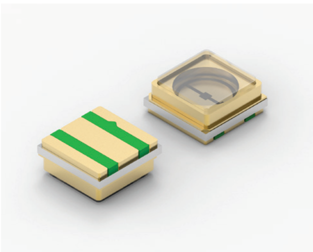

Figure 1 Würth Elektronik eiSos WL-SUMW UV-C LED with 275 nm wavelength. The 15335327BA250 LED is suitable for small disinfection targets while the 15335327BA252 product has a higher power for disinfection on a larger scale.

However, UV-C LEDs do have significant advantages. They do not contain hazardous materials such as Mercury (Hg), they do not need long warm up times i.e. they turn on immediately and are suited for frequent on/off switching. Additionally they are not vibration/shock sensitive and are relatively small compared to gas discharge lamps which makes them suitable for a variety of applications.

In recent years, research developed commercially available UV-C emitting LEDs. Even though, the initial UV-C LEDs had lower output, the year 2020 - boosted by the COVID-19 pandemic - has seen a huge increase in radiant power and drop of production price making them a more viable solution for widespread disinfection application.

The following will show the working mechanism of disinfection by UV-C LEDs, discuss the disinfection efficacy at different wavelengths, show an example of disinfection and give a few hints on safety aspects.

2 Work mechanism of UV-C disinfection

2.1 Principle of UV disinfection

Desinfection with UV-C is based on the fact that UV-C radiation can damage the DNA or RNA. This high energetic UV light can induce formation of pyrimidine dimers [2] and other damages to the DNA which can inhibit multiplication of cells such as bacterial, fungal, plant and animal cells. Similarily the UV light can damage the RNA of viruses leading to their inactivation.

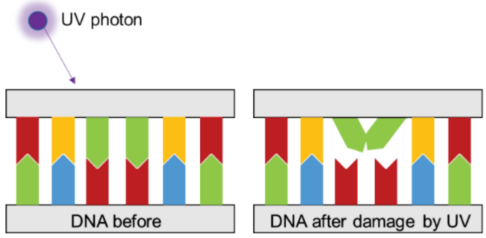

Figure 2 Schematics of DNA damage induced by UV light

2.2 Germicidal wavelengths

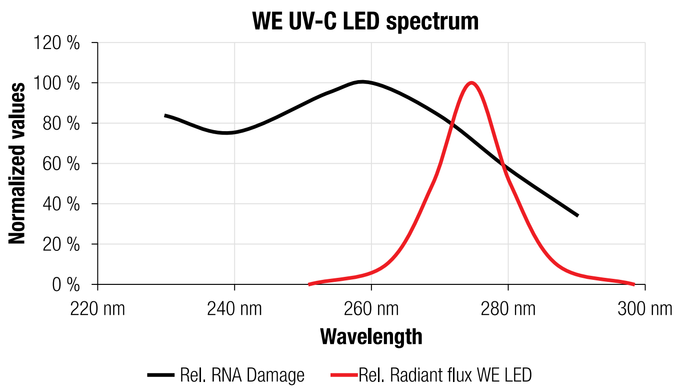

Figure 3 Wavelength dependence of RNA damage and radiant flux of Würth Elektronik eiSos LEDs.

In Figure 3, the wavelength dependent RNA damage [3] is shown. The more damage that is done to the RNA, the less capable is the virus of infecting other organisms. It is important to note that for a good sterilization result, a combination of the correct wavelength and a high amount of radiation is required. For the best sterilization result, the wavelength as well as the radiant power need to be considered. As the ratio of the optical power over the electrical power, the Wall-Plug-Efficiency (WPE) is a parameter showing how efficiently the LED can convert electrical power to optical power. The WPE of our standard 275 nm LEDs (PN 15335327BA252), is higher than other UV-C emitting LEDs with shorter wavelength. The optimal wavelength with the best sterilization efficiency will be an LED solution where both the WPE and the wavelength are as ideal as possible. An overview of the combinded sterilization efficiency of some LED solutions available on the market is shown in Figure 4. Here the combined sterilization efficiency is calculated as the product of the corresponding LEDs' WPE as well as the wavelength-dependent RNA damage. For the investigated LED wavelengths the most efficient solution for disinfection is in fact the 275 nm wavelength LED.

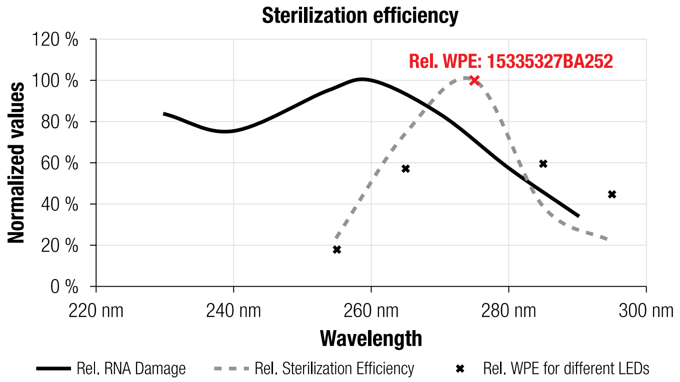

Figure 4: Sterilization efficiency (grey) as the product of RNA Damage (black) and WPE (crosses) is shown in dependence of the wavelength. Compared to other UV-C LED wavelengths available on the market, a good sterilization efficiency can be achieved with our 275 nm LED

2.3 Dose

To quantify how well disinfection works, the terminology of *log reduction* is used. A log reduction of n implies that only 10^{-n} of the previous germs survived. For example, 1 log reduction means that only 10^{-1} = 10 % of germs survived, i.e. 90 % of germs were inactivated. For 4 log reduction, 10^{-4} = 0.01 % survive, i.e. 99.99 % were inactivated. To achieve this amount of germ inactivation, a certain amount of UV-C light has to be absorbed by the germs. This amount is called the dose (Irradiance x Exposure time) and is measured in J/m². For 1 log reduction, the dose D90 is the amount of UV-C light needed to inactivate 90 % of the germs. For 4 log reduction, the dose D99.99 is needed to inactivate 99.99 % of the germs. To estimate the value for the D99.99 dose the D90 dose can simply be multiplied by 4.

Log reduction	Percentage of germs inactivated	Corresponding dose required
1	90 %	D90
2	99 %	D99
3	99.9 %	D99.9
4	99.99 %	D99.99

Table 1: Relation between log reduction, germ inactivation and dose

A number of studies have investigated the D90 dose for viruses, other germs [4] and specifically for the corona virus [5] [6] [7] [8]. Due to different experimental setup this dosage varies widely among the different research groups. To get a usable value, it is possible to get a median value of 37 J/m² [8], excluding the outliers. Even though these studies where performed with UV-C low pressure lamps we may assume a similar D90 dose for our 275 nm LED. Figure 3 shows that the damage done to the RNA is similar for 275 nm emitted by Würth Elektronik eiSos LEDs and the 254 nm mainly emitted by UV-C low pressure lamps. Additionally some publications, such as [9] show the D90 dose to be quite similar for low-pressure (LP) lamps as for 275 nm LEDs (see following table). An overview of the D90 doses for a few germs is shown in the following table:

Germ type	Information on the germ	D90 Dose (J/m²)	Lamp type
Virus			
Corona virus [8]	Corona viruses such as SARS-CoV-2	6-117540 Median: 37	LP
Hepatitis virus [10]	Causes Hepatitis	40	LP
Influenca [11]	Responsible for "The Flu"	20	LP
Adenovirus [12]	Causes the "Common Cold"	390	LP
Bacteria			
Salmonella typhimurium [13]	Can cause food poisoning	39	LP
Escherichia coli [9]	Can cause food poisoning	43 (275nm)	LED
		41 (254nm)	LP
Legionella pneumophila [14]	Can form in water supplies	17	LP
Fungi			
Aspergillus niger [15]	Can form "black mold"	1160	LP

Table 2: D90 doses for some common germs

In a German water disinfection guideline [16] the required value for water disinfection is 400 J/m² for disinfection with UV-C pressure lamps. This value is higher than the D90 dose for most typical germs and can be considered as a guideline for designing disinfection systems. As the disinfection result is depending on many conditions such as surface properties or UV-C absorbtion, studies have to be performed for each system to prove the reliable disinfection!

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When designing disinfection applications it is important to understand how to achieve a certain dose. For this, a few figures need to be understood:

- **Radiant flux:**
  The radiant flux is the total optical power output of the LED and is measured in units of [W]. This is a value that can be read from the datasheet.
- **Irradiance:**
  The irradiance is the amount of radiant flux received by a surface per irradiated area and is given in units of [W/m^2]. This irradiance can be simulated (see Section 2.4) or measured for different configurations of LEDs.
- **Exposure time:**
  The time that a surface is exposed to radiation.
- **Radiant exposure:**
  The radiant exposure or fluence is the amount of energy received by a surface. It is calculated from Irradiance x Exposure time.
- **Dose DXX:**
  The dose is the amount of energy per surface required to achieve a certain percentage of disinfection (XX% inactivation). To achive a certain amount of disinfection, the surface needs to be exposed until it received a radiant exposure that equals the desired dose.

This implies that the time needed for a desired disinfection results can be estimated knowing the desired dose and the irradiation of your system. An example is shown in the following.

2.4 Example simulation

In Figure 5 the irradiation distribution for different heigths of a PCB with 9 WL-SUMW 15335327BA252 LEDs is shown.

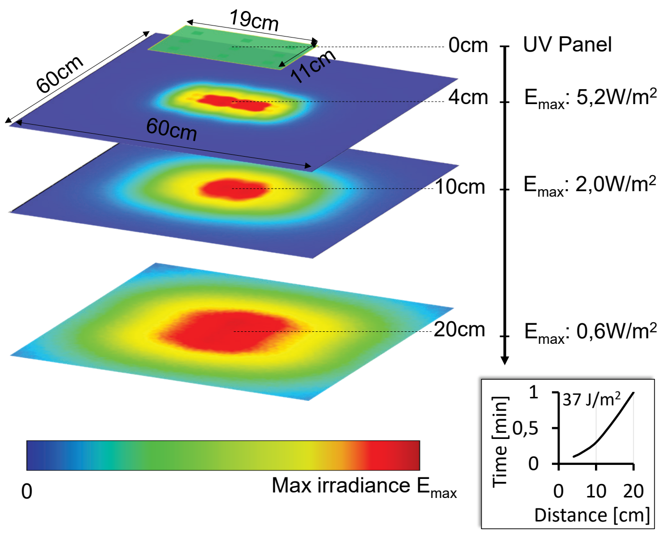

Figure 5: Examples simulation of irradiation distribution

When the height increases, the irradiated area gets larger, but also the maximal irradiance decreases. As the irradiance decreases, the required exposure time for a certain dose increases with the square of the distance (Required exposure time ∝ Distance^2) as shown in the inset for a dose of 37 J/m^2 and in the following table:

Distance	Irradiance	Exposure time required for: Dose 37 (J/m^2)	Dose 400 (J/m^2)
4 cm	5.2 W/m2	0.1 min	1.3 min
10 cm	2.0 W/m2	0.3 min	3.3 min
20 cm	0.6 W/m2	1.0 min	11.1 min

Table 3: Required exposure times for the example UV panel to achieve a certain dose, depending on the distance

This gives an indication of the required disinfection times and their dependence on the distance to the LEDs. Please note that this is just an estimation and the result depends on the LEDs and specific application. The performance in the application needs to be tested for each product separately.

3 Material degradation

UV light is known to lead to degradation in polymers [17], namely showing change of color, reduction of elasticity and strength that might result in cracks under stress. When using UVC LEDs the user has to consider using UV persistent materials such as metals and UV persitstent polymers in their applications. The UV resistance of materials may be checked by official labs [18].

According to BIFMA [19] the materials are tested with a dose of 288 kJ/m^2 which would relate to ~720 disinfection cycles with using 400 J/m^2 per disinfection cycle, or ~15 h of constant irradiation with the example UV panel from Section 2.4 at 4 cm distance. When testing the materials with this dose, some damage can be observed, whereas the amount of damage is depending on the type of material [20].

When sterilizing with UV-C light, there might be some concern regarding the generation of ozone. However this is not relevant for Würth Elektronik eiSos 275 nm LED as they emit well above the threshold for ozone generation. The generation of ozone becomes only relevant for wavelengths below 240 nm. When disinfecting water with 275 nm LEDs the light is aborbed by germs or escapes the water. The UV-C light is not stored in the water, meaning it can not do any damage after the disinfection process. This implies that the UV-C disinfected water is not harmful for consumption, but also has the disadvantage that there can be some reinfection of the water after the disinfection process.

4 Safety

UV-C light is especially potent of damaging the DNA of all cells, including human, animals and plants. Furthermore, UV-C radiation is naturally blocked by the ozone layer and does not reach the earth's surface. This is why organsims on earth did not develop any repair mechanisms for the damage caused by the UV-C light. Because of this reason, UV-C is so potent for killing germs.

Figure 6 UV Warning symbol according to IEC 60417-6040.

However this also implies, that it is especially dangerous for our eyes and skin, causing long term damage such as skin cancer even long time after the exposure [21]. Great caution must be exercised when implementing UV-C light in applications. According to the maximum allowed dose per 8 h work day must not be higher than 30 J/m^2. For continuous exposure this implies that the irradiation should not be more than 0.001 W/m^2.

Appropriate personal protection equipment and shielding have to be applied to ensure product safety. The following example gives an idea of what the requirements for the shielding look like.

4.1 Example calculation of shielding material:

For the example UV panel shown above at a distance of 20 cm the maximum irradiation is 0.6 W/m^2. To get below the maximum allowed irradiance of 0.001 W/m^2 assuming a long time exposure, the shielding must have a transmission smaller than $\sim 10^{-3}$. However, it is highly recommended to reduce the transmission of the shielding material even further, as the damage done by UV-C radiation is cumulative over a long time scale [21]. It has to be noted, that the irradiance is highly dependent on the distance to the UV-C source. In our example, if the distance between UV panel and skin/eyes is 4 cm, the transmission of a shielding material should already be smaller than $\sim 10^{-4}$. For 1 cm distance the transmission should be below $\sim 10^{-5}$.

4.2 Safety considerations

Several documents cope with the safety relating to UV-C radiation such as [22], [23], [24], [25] and [26]. To give a brief overview and tips for working with UV-C LEDs, some key points are summarized here:

- The exposure of the end user (eyes and skin) must be kept to a minimum. The limit is less than 30 J/m^2 per 8 h work day.
- Products using UV-C must be marked with appropriate warning signs and an appropriate instructional safeguard and user manual must be included.
- Degradation of materials exposed to UV-C light needs to be considered.
- If too much UV-C light is leaving the application, such as in handheld lamps, all people that are potentially exposed need appropriate training and sufficient personal protection equipment such as face shields, gloves and protective clothing.

5 Summary

UV-C LEDs are an exciting new technology for disinfection purposes such as corona virus inactivation. But they will continue to play a big role in preventing future pandemics and coping with healthcare issues such as multiresistant germs. For general reduction of germs in many consumer applications, in air filtration systems, in water supplies and in food industry, the UV-C LEDs will continue to be in high demand long after the pandemic is over.

This application note explained the working mechanism of disinfection with UV-C and gives hints for the required radiation doses for different germs found from various publications. Furthermore it gives a calculation example using Würth Elektronik eiSos UV-C LEDs and also some tips and references on UV-C safety in your application.

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A. Appendix

A.1. Literature

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