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Whitepaper

Designing Disinfection Systems with UVC LEDs

Recent progress in the performance of UVC LEDs have more and more OEMs seriously considering them for multiple applications across their product portfolio.

The small footprint of UVC LEDs have always presented a design advantage over mercury bulbs for disinfection, as has the sustainability of the mercury-free technology. However, recent advances in power output and lifetime create a compelling advantage over the legacy technology. The lifetime of UVC LEDs has jumped from 5,000 hours a few years ago to over 20,000 hours. This means that design engineers and product managers can now look at the benefits of maintenance-free systems and what that means to their customers and their bottom line.

As more companies turn to UVC LEDs, we're seeing the innovative ways designers can take full advantage of the footprint, power, and lifetime benefits of these devices. However, designing something truly game-changing requires an understanding of how to best leverage these benefits. The design engineer needs to consider a few key parameters: target microbe, disinfection requirement, and thermal management system design.

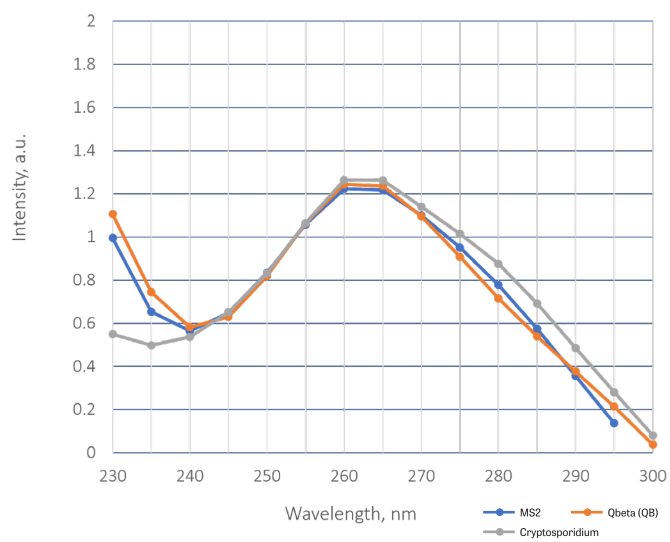

FIGURE 1: Absorption curves for common target microbes.

Understanding Target Disinfection Performance

In UV disinfection, short wavelength ultraviolet (UVC) light in the range of 250 to 280 nm disrupts the DNA of microorganisms rendering them unable to reproduce. The action spectrum for bacteria is commonly reported and shown as a response from 200 to 300 nm with a peak between 265 to 267 nm wavelengths, with some variation across species (Figure 1). Low-pressure mercury arc lamps are a common way of accessing the germicidal portion of the irradiation spectrum as they emit a discrete wavelength at 254 nm. Although this is not the optimal germicidal wavelength, there is sufficient emission to disrupt DNA and the standard in water treatment and reuse industries.

LEDs can be tuned by the manufacturer to emit light at a specific wavelength. This is seen by the range of LEDs available for different sensing applications where a specific wavelength is used for spectrophotometry. It's important to understand the target microbe, or biodosimer, that is being used to design your system and its spectral response. A biodosimer is a surrogate microbe used to measure the performance of a system to ensure it delivers the disinfection performance for the application. These are often defined by industry standards such as NSF or EPA, however some manufacturers may prefer to use a specific microbe based on their own internal requirements.

Once the target microbe is selected, it's important to understand the dosage required to meet the disinfection target.

Dosage is the energy required to reach a specific log reduction of a target microbe. Dosage is a function of UVC energy over time, and thus it depends both on the energy at the specific wavelength and the time of exposure. It is possible to use a lower power LED, or one of a less ideal wavelength, if you have more time allowed for disinfection—such as low flow applications. In water disinfection, the power at the specific wavelength will directly relate to the ability to disinfect higher flows of water. Table 1 shows the dose required at 254 nm for different log reductions of the microbes in Figure 1.

Table 1: UV Dose response based on 254 nm

Microbe	1 LRV	2 LRV	3 LRV	4 LRV
MS2	16 mJ/cm^2	34 mJ/cm^2	54 mJ/cm^2	78 mJ/cm^2
Q Beta	11 mJ/cm^2	22 mJ/cm^2	34 mJ/cm^2	46 mJ/cm^2
Cryptosporidum	4 mJ/cm^2	9 mJ/cm^2	13 mJ/cm^2	17 mJ/cm^2

SOURCE: https://scholar.colorado.edu/downloads/rn301175t

Using the dose from Table 1 and the spectra from Figure 1, you can calculate the dosage required at your specific wavelength, then consider the intensity and residence time to achieve the system goals. In general, higher flow rates will require more energy whereas maintaining a disinfection level require less. Using this information will enable you to calculate the on time—and thus the overall product lifetime before maintenance is required.

LEDs are a solid-state light source, meaning that they reach full intensity less than a millisecond after turning on and the number of on/off cycles do not impact the lifetime of the light source. The lifetime of many commercial UVC LEDs today is enough to last the lifetime of most consumer products—7 – 10 years. However, when designing the system you need to consider the power required at end of life so that the disinfection performance will be adequate for the full lifespan of the product.

Basic Thermal Management

The performance of a device listed on the data sheet is captured under highly controlled lab conditions when testing a single LED. However, in practice most systems will require multiple LEDs and thus the performance relies on proper thermal management to meet the specifications on the data sheet. In the case of water disinfection systems, many OEMs choose to employ an external cooling system—either with water or air—whereas mercury lamp-based systems will often use the process water to cool the system, which commonly results in a first hot glass of water.

When forward voltage is applied across the junction of an LED, forward current flows through the LED and electrical power is dissipated as both light and heat. Current commercial UVC LEDs dissipate most of their power in the form of heat as the wall plug efficiency is generally in the 3-7% range, therefore for the heat generated is regarded as approximately equal to the power dissipation.

The junction temperature of an LED increases with the generation of heat, with the rate of increase dependent upon the amount of heat that is dissipated to the ambient. The thermal resistance from the junction to the thermal pad of an LED is fixed by the materials used in the package by the LED manufacturer. Application designers have flexibility in the selection of the PCB, the heat sink and the thermal interface material between the PCB and the heat sink.

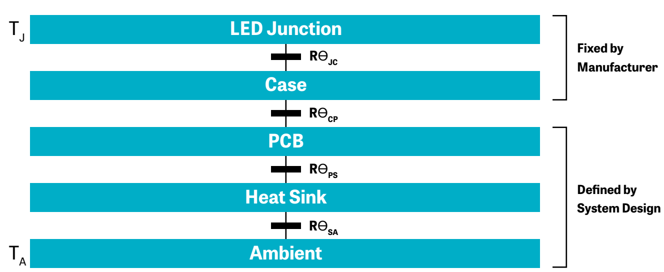

FIGURE 2: Illustration of thermal model of LED assembly

Some simple rules in heat sink design or selection:

- When soldering the LED to the PCB, minimize the thickness of the interface materials between the PCB and the heat sink (i.e. the distance the heat must travel).
- Use a heat sink with a large surface area.
- Use metal core PCB for LEDs.

It's generally accepted that using materials that have a high thermal conductivity (k) will ensure a better design and more predictable performance. However, this must be considered within the overall design costs and LED assembly budget for the product. For example, although copper is a better thermal conductor, aluminum is frequently the material of choice for heat sinks due to cost and weight considerations.

Now that we understand the key parameters when designing with UVC LEDs, we will look at how to approach the design of a POU water system considering two different commercially available LEDs.

Example Application: Point-of-Use Drinking Water System

This example system treats water at 2 liters per minute targeting a 3 log reduction of MS2. The capacity of the system is 6000 liters per year, with a product lifetime of 10 years. Based on typical on-demand operation of a UVC LED-based system, this would indicate an LED lifetime of 500 hours at end of life. The specifications of the two LEDs considered can be seen in Table 2.

Table 2: Commercial UVC LED Specifications

	LED A	LED B
Peak Wavelength	265 nm	280 nm
Power Output	80 mW	110 mW
Typical V_F	7 V	5.8 V
Input Current	500 mA	350 mA
Thermal Resistance	7 °C/W	9.4 °C/W
Max Junction Temperature	115 °C	110 °C

As you can see in Figure 1, a system targeting MS2 would need approximately 40% more power output if it was using UVC LEDs with a peak wavelength at 280 nm as opposed to using devices with a 265 nm output. According to Table 1, the dosage required to achieve a 3 log reduction of MS2 is 54 mJ/cm^2 at 254 nm, thus using the absorption curve, we can calculate the required dosage at 265 nm and 280 nm and end of life LED power per Table 3.

Table 3: Dosage for 3 log reduction of MS2

	Absorption Coefficient	Dosage Required for 3 log reduction (mJ/cm^2)	EOL Power (mW)
265 nm	1.23	42	203
280 nm	0.78	66	319

Power calculation assumes UVT of 70%

This can impact not only the number of LEDs required, but also the footprint, system power, and thermal management system design. Given that lifetime of UVC LEDs has improved, 500 hours of on-time in a system means that the end-of-life power can assumed to safely be L70.

Table 4: Power required at system beginning of life

	End of Life (EOL) Power at L80 (mW)	Beginning of Life (BOL) Power at L80 (mW)
265 nm	203 mW	253 mW
280 nm	319 mW	399 mW

With the beginning of life power requirements for our two system considerations, we can calculate 1. Number of LEDs needed based on commercially available products and 2. Basic requirements for the thermal management system. For the purposes of this paper, we are assuming that the reactor design would enable for all the LEDs to be arranged on a single reactor endcap.

Table 5: LEDs required to meet beginning of life requirement

	Single LED Output	Total LEDs Needed
LED A	80 mW	4
LED B	110 mW	4

For the thermal calculations, we need to consider the specifications of the LEDs in Table 2. Using these parameters, we can look at the impact on thermal management design, which will include the selection of thermal paste, PCB and heat sink. The ability to dissipate the heat will ensure that the LED assembly performs as expected for the lifetime of the product.

If we take the inputs from the data sheet, and use some values for a standard solder paste, PCB and heat sink, we can see the results in Table 6.

Table 6: Thermal calculation with standard materials

	LED A	LED B
# of LEDs	4	4
LED V_f	7 V	5.8 V
LED Current	500 mA	350 mA
LED Thermal Resistance	7 °C/W	9.4 °C/W
Solder Thermal Resistance	1 °C/W	1 °C/W
PCB Thermal Resistance	3 °C/W	3 °C/W
Heat Sink Thermal Resistance	2 °C/W	2 °C/W
T_a	22 °C	22 °C
ΔT	98 °C	62 °C
T_j	120 °C	84 °C
Typical LED Power	80 mW	110 mW
LED Power	53 mW	87 mW
Thermal Derating	0.35 %/°C	0.35 %/°C
Total Power of 4 LED Assembly	**214 mW**	**350 mW**

Without considering the power required at beginning of life, both of these assemblies would seem to meet the application requirements of 203 mW and 319 mW respectively (Table 3). However, neither would deliver the power required for beginning of life (Table 4)—regardless of the wavelength.

However, if we lower the temperature of the ambient, as is typical of a water system, and employ more advanced materials, we can see at which level the total power of the assembly will match the application requirements for disinfection power in Table 7.

Table 7: Thermal calculation optimized to meet BOL power

	LED A	LED B
# of LEDs	4	4
LED V_f	7 V	5.8 V
LED Current	500 mA	350 mA
LED Thermal Resistance	7 °C/W	9.4 °C/W
Solder Thermal Resistance	1 °C/W	1 °C/W
PCB Thermal Resistance	2 °C/W	1 °C/W
Heat Sink Thermal Resistance	0.5 °C/W	0.05 °C/W
T_a	20 °C	20 °C
ΔT	63 °C	30 °C
T_j	83 °C	50 °C
Typical LED Power	80 mW	110 mW
LED Power	63 mW	101 mW
Thermal Derating	0.35 %/°C	0.35 %/°C
Total Power of 4 LED Assembly	**255 mW**	**402 mW**

You can see from these calculations how the lower thermal resistance of the 265 nm LED enables for smaller tweaks in the thermal resistance of the system to reach the application requirements. The 280 nm LED requires more premium system materials to achieve the level of power required for disinfection at this particular wavelength. Typically, the lower the thermal resistance of the material, the more expensive it will be. For example, to achieve the thermal resistance of 0.05 in the second design for LED B, the heat sink is using active cooling techniques such as water cooling.

When designing UVC LED-based systems, sometimes designers need to go beyond just values on a data sheet when comparing different products. The application requirements around microbe selection and total cost of the system design will help inform the selection of the proper product. Sometimes the LED that may look less ideal on paper may lead to a simpler design that meets cost targets.

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