

Germicidal Power

As UVC LEDs gain traction in disinfection applications, high volume manufacturers are requesting a more systematic approach for specification of germicidal output power. This application note details how Crystal IS has addressed this request by focusing on The distinctions of UVC LED power and what is meant by “germicidal power.” The importance of the spectral response of solid-state sources, such as UVC LEDs, in contrast to the monoand poly-chromatic output of traditional mercury-based plasma sources is highlighted. Implications for specification work when designing with UVC LEDs are reviewed.

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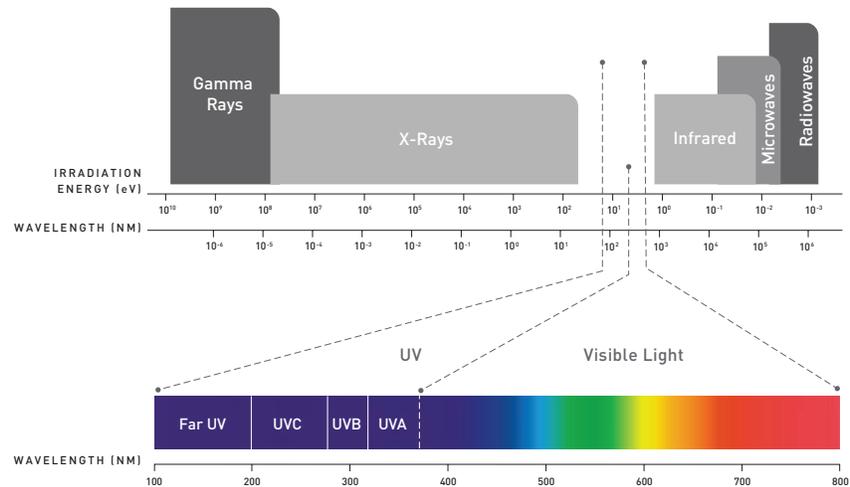
Introduction

Ultraviolet (UV) disinfection has gained popularity over chemical disinfection methods because of the increased awareness of chemical-resistant microbes, absence of harmful by-products, and taste perceptions. UV disinfection relies on radiation emitted in the wavelength range of 250 nm to 280 nm (UVC) to inactivate pathogens. Commercial UV technology solutions developed over the past 30 years using low and medium pressure mercury-based lamps have been hampered by the use of fragile quartz sleeves, long warm up times, limited switching cycles, and the toxicity risk of mercury. There is tremendous development in semiconductor-based UVC Light Emitting Diode (LED) technology, towards efficient, cost effective, and an environmentally friendlier alternative to traditional UV technology. In contrast to the discrete line emission at particular wavelengths of traditional gas sources, the emission of Light Emitting Diode (LED) sources is a relatively narrow band spectrum where the position and width of the peak depend sensitively on the details of LED manufacture. These differences in emission spectra require a new methodology to account for disinfection effectiveness.

The spectral response of UV light sources is an important distinction to understand when working with this technology. Medium pressure mercury lamps are polychromatic with emissions represented as multiple peaks across a wide range. Low-pressure mercury lamps are monochromatic light sources whose emissions are typically represented as line spectra since the typical Full Width at Half Maximum (FWHM) of the emission is so narrow (less than approximately 1 nm). Although the emission curve of LEDs is not as narrow as low-pressure mercury lamps, with a typical FWHM of 15 nm, they are considered monochromatic light sources with an emission represented as a smooth curve. The differences in the emissions of these light sources can be seen in Figure 2.

What is UVC and the Germicidal Range?

UV light represents the portion of the sun's energy that falls between visible light and x-ray on the electromagnetic spectrum. This light spans from 100 and 400 nanometers (nm) in wavelength, and can be further divided into UVA, UVB, UVC, and VUV. The UVC portion represents wavelengths from 200 nm-280 nm, with the range from 250 nm - 280 nm considered as the germicidal range (Figure 1).

FIGURE 1: ELECTROMAGNETIC SPECTRUM

Germicidal UV light deactivates the DNA of bacteria, viruses, and other pathogens that can cause infection and disease. Specifically, the UVC radiation penetrates the cells of these microbes, damaging the nucleic acid and rendering them unable to reproduce. Without the possibility of reproduction, the microbes are rendered inactive. A generic action spectrum for bacteria is often reported and shown as a response from 200 nm - 300 nm with a peak between 265 nm - 267 nm wavelengths. In actuality, there is a range of susceptibility for various microbial species, which depend on both extracellular and intracellular environments. Optimum wavelength can depend on the particular action spectra of the unique microbe. As a result, the most effective designs for UV disinfection devices and reactors require careful microbiological study and verification using target microbes.

COMMON UV SOURCES

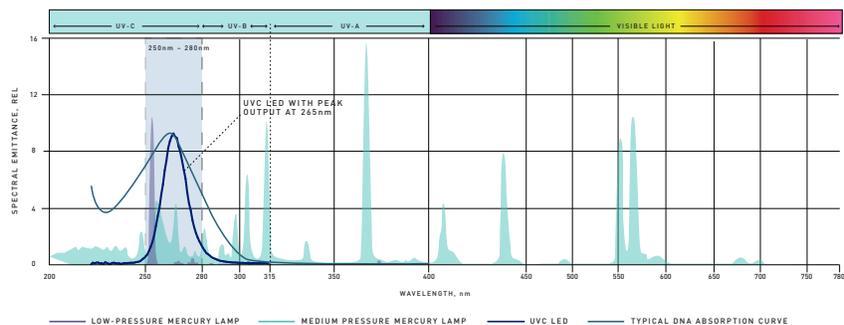
There are several sources that can be used to emit UVC light—the most common are:

- > Low-pressure mercury lamps
- > Medium pressure mercury lamps
- > Light Emitting Diodes (LEDs)
- > Xenon flash lamps
- > Deuterium lamps

Of the technologies mentioned above, the most commonly used for UV disinfection are low and medium pressure mercury lamps. In low pressure mercury lamps, almost all the light emitted is generated at 253.7 nm in form of a monochromatic line spectra.

However, this emission at 253.7 nm intersects the absorption spectra of the microbe below its peak absorption. Therefore, low-pressure mercury lamps are not optimized for efficient DNA inactivation. On the other hand, medium pressure mercury lamps are polychromatic, emitting light across many wavelengths, thus not all the light emitted is used for germicidal purposes. Although mercury-based lamp systems are useful for disinfection, their outputs are fixed by the reaction mechanisms of mercury and they do not provide maximum efficiency.

FIGURE 2



Comparison of emission spectrum of low-pressure mercury lamp, medium pressure mercury lamp, UVC LED and typical DNA absorption curve. The curve depicted for the UVC LED represents a typical commercial UVC LED for disinfection applications.

UVC LEDs are gaining popularity in disinfection applications due to their small form factor, simple DC electronics, low power operation, and environmental friendliness. As seen in Figure 2, the emission of UVC LEDs is a continuous spectrum across a specified range. The peak of the emission may vary within the range and can be tailored for greatest overlap of the most critical wavelengths for optimizing disinfection.

Determining Optimal Power for Targeted Disinfection

The amount of UVC radiation applied to a given volume over a specific time period needed for disinfection in a particular system is commonly referred to as the required UV Dose. Some microorganisms are less resistant than others to UVC radiation and thus require less exposure time or intensity, while others require more for adequate target inactivation. The UV Doses for various common microbes are listed in the Crystal IS application note AN002, UVC LEDs for Disinfection.

UV Dose is composed of two factors—the intensity of the light and the length of exposure to radiation—and can be calculated as follows:

$$UV\ Dose = UV\ Intensity\ (I) \times Exposure\ Time\ (t)$$

UV light intensity is defined as power output generated by the light source in the UVC range and is represented in milliwatts per centimeter squared (mW/cm^2). Exposure time (t) is measured in seconds (sec) and dose is typically represented in millijoules per centimeter squared (mJ/cm^2).

Low-pressure mercury lamps emit a single output at 253.7 nm, the total output power of the lamp is equivalent to the output power in the UVC range, albeit at a non-optimal wavelength. Medium pressure mercury lamps emit a broader range of wavelengths that include the germicidal range, but also unnecessary wavelengths (as shown in Figure 2). In fact, only about 20–30% of the light is emitted in the UVC range, with the unwanted wavelengths creating byproducts (some harmful) and wasted energy in disinfection systems. On the other hand, the continuous spectral response of UVC LEDs is largely within the desired UVC range, which allows for a more efficient system.

Determining Required Germicidal Power

There are several methodologies one could invoke to best estimate the germicidal power anticipated from a light source. The most accurate method would involve first knowing the specific microorganism to be inactivated and assess the integrated power of the light source over the precise wavelength range of the microbe's action spectrum. There is a significant body of literature and several relevant reviews of the most common pathogens (bacteria, virus, protozoa, spores) and their related action spectra and associated UV dosage (see Appendix).

In practice, established standards committees for key industries set guidelines to limit the scope of microbiological testing to a practical range for certification purposes. Often this is done by setting a challenge microorganism, or biosimulant, as the most resistant species and then establishing guideline dosage inactivation criteria.

Standards organizations and/or manufacturers identify target organisms for disinfection systems which are of concern for public health. Systems are designed to irradiate these target organisms to be effective. However, in practice, testing designs using these target organisms opens a host of safety risks. For that reason, designers perform microbiological testing with select test or challenge organisms that mimic the behaviors of the target organisms. These challenge organisms (ex. Bacteriophage MS2, *B. subtilis*) are typically safer and more stable than their harmful counterparts (ex. *E. coli*, *Giardia*, *cryptosporidium*), making them more suitable for validation tests.

Once an action spectrum is determined for the microbe (or in some cases a cocktail of microbes) of particular relevance, the cross product of that spectra with the emission spectra of the particular light source is the best estimate of what one would consider germicidal power. Crystal IS designates the resultant spectra from this cross product as P_o .

P_o Calculation with ÖNORM Weighting

For illustrative purposes, an example is noted here of calculating P_o using the ÖNORM standard spectra of *B. subtilis*. To clearly demonstrate the result of this calculation, the example uses an extreme case of an LED with a less than perfect emission spectrum. This is not a typical representation of commercially available UVC LEDs. The baseline or standard spectra of the biosimulator for the system, such as the *B. subtilis* spectrum for water disinfection (Figure 3A), can be convoluted with the light output spectrum of a UVC LED (Figure 3B). The integrated portion that is generated based on the combination of the two spectra (Figure 4) determines the effective germicidal power output for that UVC LED.

To deal with discrepancy related to actionable wavelengths, work was carried out to observe the disinfection effect as a function of wavelength and published in Austrian National Standard ÖNORM M 5873. The work carried out by the standards committee is included in UV Disinfection Guidance Manual (UVDGM 2006) and German Association of Gas and Water (DVGW 2003) to illustrate dosage requirement as a function of wavelength. The standard from ÖNORM involved several microbes tested using low-pressure mercury systems. Here, both *B. subtilis* and MS2 are biosimulators for UV reactor validation due to their high resistance to UV photons. The approach exposed *B. subtilis*, a challenge organism for drinking water disinfection systems, to UVC radiation at different targeted wavelengths using a radiation lamp and a wavelength cutoff filter. The experiments were performed between the wavelengths of 240 nm and 352 nm. The resultant data was plotted for the log reduction of the microbe as a function of dosage. This outcome (Figure 3A) is a single absorption spectrum for *B. subtilis* to use as a standard for the spectral sensitivity of such microbes to UV light at a reference of 253.7 nm (low-pressure mercury emission).

FIGURE 3A

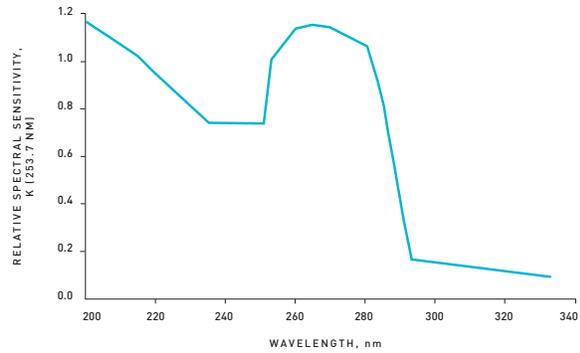
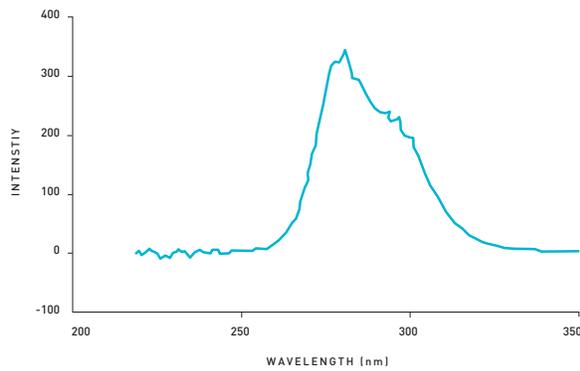
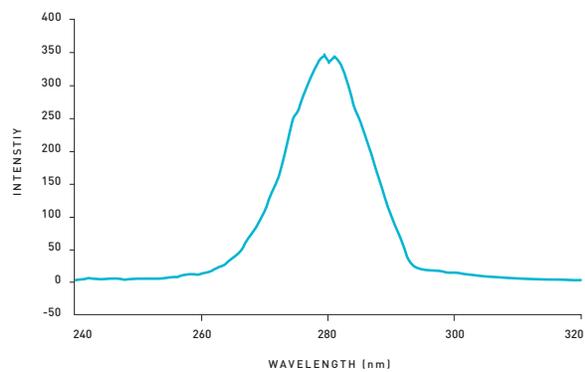


FIGURE 3B



Microbe action spectrum (A) and actual LED spectrum* (B) are multiplied (convoluted) to obtain the net effective germicidal power. *The UVC LED spectrum shown is an extremely imperfect emission example for demonstration purposes—not characteristic to commercially available UVC LEDs.

FIGURE 4



Effective germicidal power plot obtained after convolution.

Table 1 shows the comparison of the total power (P_t) of the UVC LED (Figure 3B) with the germicidal power (P_o) of the resulting convolution (Figure 4).

TABLE 1

WAVELENGTH (nm)	TOTAL POWER, P_t (mW)	GERMICIDAL POWER, P_o (mW)
278	10	5.5

In this particular example, the data shows that approximately 55% of the total power would be effective for disinfection compared to the total power emitted by the diode. This approach has the effect of weighting the measurement parameter toward the useful emission which matches the pathogen standard selected. As a result selecting “peak wavelength” as a distinct criteria no longer becomes necessary and is not as accurate since the “peak wavelength” does not capture the details of the LED spectrum. Specifying the germicidal power (P_o) is a more accurate way of describing the output power of a diode for UV disinfection applications.

Total Power Versus Germicidal Power— Comparison of Two Diodes with the Same Total Power

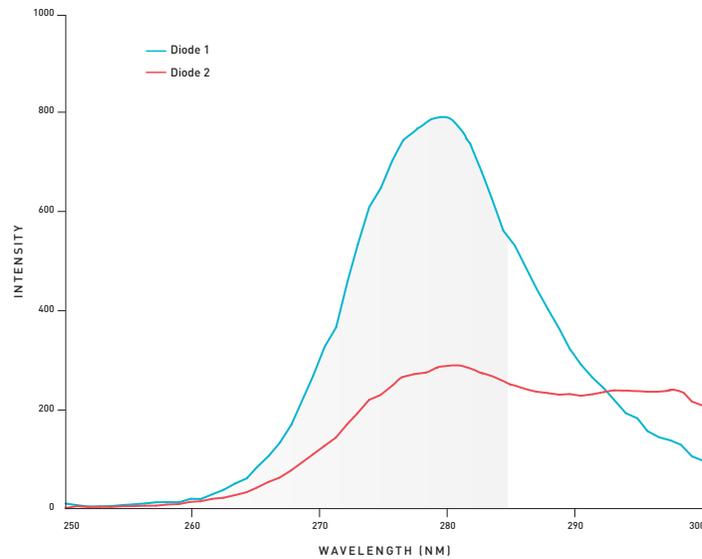
Calculating the germicidal power (P_o) of a light source removes the peak wavelength criteria. This normalizes the power output and allows for a more efficient system by designing to the light output that is effective for disinfection. The following examples show how P_t and P_o can be very different, even though there may be no difference in peak wavelength. Two UVC LEDs with the same peak of 278 nm have the same total power output of 23.9 mW. After performing PO calculations using ÖNORM challenge microorganism, it is apparent that a large discrepancy exists in the PO for the two diodes.

TABLE 2

	PEAK WAVELENGTH (nm)	P_t (mW)	P_o (mW)
Diode 1	278	23.9	22.2
Diode 2	278	23.9	16.5

Although both have 23.9 mW total power output, the germicidal power of Diode 1 is higher than that of Diode 2 by 5.7 mW—a significant difference. By examining the spectra of these two UVC LEDs (Figure 5), the reason for the difference in germicidal power is clear. The convolution calculations eliminate the output outside the shaded area under the curves on Figure 5. Figure 3a shows that the bulk of germicidal activity for *B. subtilis* is from 250 nm - 285 nm. This is similar to other target microorganisms such as *E. coli*, *Giardia*, *cryptosporidium*, and others. (Reference articles that include this data can be found in the Appendix.) So, although both diodes have the same peak and total power, Diode 1 with the more perfect bell shaped curve emits more germicidal power.

FIGURE 5

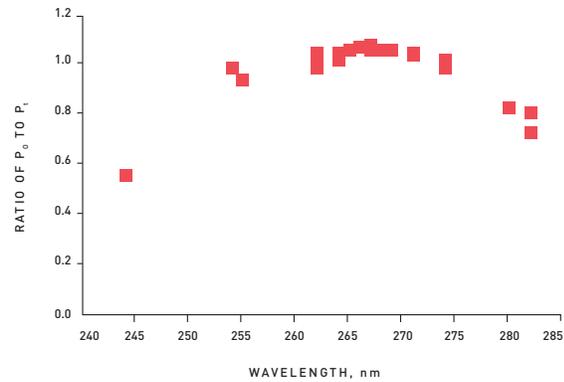


Spectra of two diodes and gray area showing the area of germicidal activity. The UVC LED spectrum for Diode 2 shown is an extremely imperfect emission example for demonstration purposes—not characteristic to commercially available UVC LEDs.

Designing for Manufacturing Production

Throughout product development or design it may be the engineer's preference to observe each spectrum of an individual light source in order to determine optimum benchmark performance criteria. However, high volume manufacturers are requesting a more systematic approach for specification of germicidal output power. This approach of convolution has that desired effect.

The Crystal IS manufacturing process is focused on target peak wavelengths for the highest germicidal power outputs possible. Figure 6 shows the impact of wavelength of discrete diodes on the ratio of P_0 to P_t , where P_0 is calculated via $\dot{O}NORM$. Diodes manufactured with peaks at the edges of the UVC range have a lower ratio of P_0 to P_t , and thus less effective germicidal power. While diodes that peak in the optimum germicidal range of 255 nm - 275 nm have very little difference between total power and germicidal power.

FIGURE 6

Shows the effect of wavelength on the power output ratio of P_o to P_i .

Conclusion

Crystal IS uses an industry-recognized action spectrum to determine the germicidal power (P_o) of their disinfection-grade diodes. Using this method, engineers can focus on disinfection power requirements rather than the variations involved with the total power and wavelengths. In this note *B. subtilis* is used as an example baseline for drinking water disinfection systems to determine the UV Dose requirements. Other applications may use the action spectra of other microbes to determine relevant P_o values. While in complex microbiological systems there is not a single approach that fits all needs, this is a step forward in simplification that allows the engineer to create reasonable designs for manufacturability.

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