Accurately Measuring UVC Dose in UVGI Applications

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Scope

This white paper explains the various factors that can impact accurate measurement of UVC ultraviolet light power and dose. Also included is an explanation of how significant differences can occur between UVC dose and the efficacy of pathogen neutralization in UVGI applications.

Power vs Dose

First, it's important to understand the difference between power and energy. Joules (J) is a unit of energy, while Watts (W) is unit of power (rate of energy delivery). Expressed as a formula:

1 Joule = 1 Watt x 1 second

UVC dose is a measurement of UVC energy delivered per unit area (typically one square centimeter or cm^2). That total dose can be the result of low UVC power for a long duration, or high UVC power for a short duration. For example:

- $50mJ/cm^2$ can be produced by $50mW/cm^2$ for 1 second
- $50mJ/cm^2$ can be produced by $1mW/cm^2$ for 50 seconds

A real-world example may further clarify. Getting a sunburn is the result of excessive sunlight dose. Stepping into direct sunlight briefly doesn't create a sunburn – one must spend a sufficiently long period of time in the sunlight to create a sunburn. In both cases the sunlight power is the same, but the doses are different because the durations are different.

Factors Affecting UVC Measurement

Measuring UVC power is conceptually simple but obtaining accurate measurements can be difficult. Depending on the measuring configuration, various laboratory UVC power meters can produce results that differ by more than a 2:1 ratio! This usually begs the question, "which meter is producing the most accurate result?"

UVC Wavelength

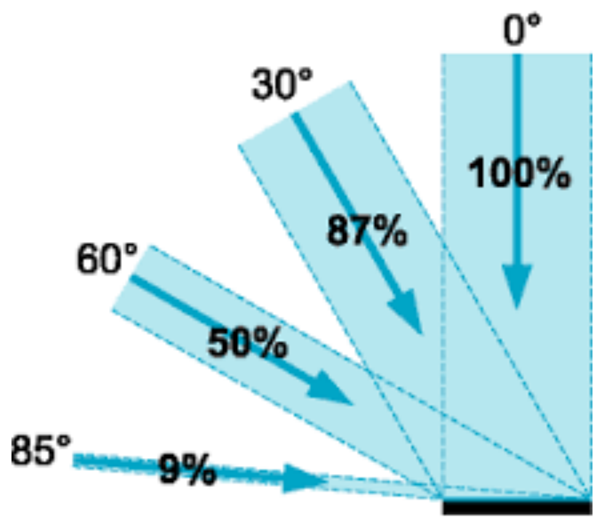
For many years most UVC lamps have used low-pressure mercury vapor lamps. These lamps produce UVC at 253.7nm wavelength (usually rounded to 254nm), and as a result, nearly all UVC power/dose meters are calibrated at this wavelength.

In recent years UVC LEDs have become available, and although they are far less efficient and more costly than mercury vapor lamps, they are gaining popularity due to their small size and absence of hazardous mercury. UVC LEDs produce light at various wavelengths, but most are in the range of 265nm to 275nm.

The sensors used on UVC power/dose meters all include an optical filter to make them insensitive to light outside the UVC band. Some of these filters are narrow-band and produce significant sensitivity variation when a UVC wavelength other than 254nm is used. For instance, a 265nm LED may result in power measurement similar to that of a 254nm mercury vapor lamp, but a 275nm LED may have meter sensitivity reduced by more than 50%.

<u>Cosine Correction</u>

The power a surface receives from a light source is dependent on the angle of the light rays. A light source with rays perpendicular to the surface will have 100% effectiveness, but light rays hitting at an angle will have less effectiveness. This is the result of Lambert's Cosine Law.



Lambert's Cosine Law

Another real-world example may be helpful. If you're sitting facing the sun, the sun's rays hit your forehead at a nearly perpendicular angle. This means that you'll most likely sunburn your forehead, but the sides of your face may not be sunburned because the sun's rays are hitting at a significant angle. The sides of your face receive less sunlight dose due to the cosine law.

To accurately measure the UVC power/dose on a surface, a meter with good cosine correction must be used. This is important because the irradiated surface may not be directly facing the UVC source, and/or some UVC light be reflected from other surfaces (e.g., walls, ceilings and floors).

Most UVC power/dose meters do not provide accurate cosine correction over the full 0° to 90° light angle, and specification details are generally not available. This is believed to be the primary source of measurement errors when comparing different power meters in the real world. In a UVC disinfection application, light may enter the sensor from a variety of directions (some direct and some reflected); consequently, a meter with poor cosine correction will probably display a lower power/dose value than it should.

Because of significant variation in cosine correction performance, **the only consistent 'apples to apples' method of calibrating or comparing UVC meters is by using columnated UVC light that enters the sensor at 0° (perpendicular).**

UVCense™ dosimeters have been confirmed to possess nearly perfect cosine correction within a 110° (±55°) cone above the sensor. UVC sensitivity drops off rapidly as the light angle exceeds ±55°, but this behavior has benefits in Ultraviolet Germicidal Irradiation (UVGI) applications (explained later in this white paper).

<u>Ambient Light</u>

As mentioned above, all UVC sensors use some type of filter to block ambient visible light. However, these filters and sensors are not perfect, and under certain conditions the meter reading may be higher than expected in the presence of visible light.

It is impractical to make UVC sensors completely immune to visible light due to extremely large dynamic range requirements. Direct sunlight delivers approximately $100mW/cm^2$ power to a surface. When attempting to measure UVC as low as $1\mu W/cm^2$ in the presence of direct sunlight, the filter must provide a visible light rejection ratio of more than 100,000 : 1 – a figure that is impractical with common filters and sensors. As a result, a laboratory UVC power meter in direct sunlight may read UVC power in the range of $300\mu W/cm^2$ even though no UVC is being externally delivered.

In applications with normal room lighting, visible light rejection is usually sufficient to prevent measurement corruption. However, inaccurate UVC measurements will likely result if the UVC sensor is positioned where it is exposed to direct sunlight through a window.

UVGI Efficacy in the Real World

Due to COVID-19, Ultraviolet Germicidal Irradiation (UVGI) has rapidly gained acceptance as an effective way to mitigate pathogen transfer from person to person. UVGI is now being utilized in two primary methods: irradiating air and irradiating surfaces.

Recent research has shown that aerosols (small particles carried by air) are the most prevalent means for SARS-CoV-2 virus transfer between people (this may not be true for other types of pathogens). Consequently, UVGI systems that irradiate aerosols have also become popular. These include upper air UVC systems that irradiate air near the ceiling in a room (with assumed low UVC doses to people in the room), and in-duct UVC systems that irradiate aerosols inside the HVAC system. Measuring the disinfection efficacy of such systems is challenging because the dose received by aerosols is affected by various factors such as airflow patterns in a room and airflow rate through HVAC ducts.

Disinfecting surfaces is also important to prevent person-to-person pathogen transfer through surface contact. Surface UVC dose is easier to measure with an accurate dosimeter, but it also has some important considerations that affect disinfection effectiveness (efficacy).

Log Reduction Value

Each pathogen has its own unique characteristics and Log Reduction Value (LRV) for neutralization, and an ever-growing list of pathogen characteristics is being compiled.[1] Staphylococcus aureus is a bacteria pathogen commonly found in HAIs. The table below shows the LRV dose values for this specific pathogen using 254nm UVC light:

LRV	1	2	3	4	5
Neutralization	90%	99%	99.9%	99.99%	99.999%
Dose in mJ/cm^2	4.4	5.8	6.4	7.3	9.0

254nm UVC Dose Levels by LRV for Staphylococcus aureus[1]

As shown above, Staphylococcus aureus requires a UVC dose of $7.3mJ/cm^2$ to achieve 99.99% (LRV4) neutralization (a commonly used disinfection target). As shown in reference 1, some pathogens require substantially higher dose to achieve LRV4; however, most common pathogens will achieve an LRV of at least 4 with a dose of $50mJ/cm^2$. Consequently, $50mJ/cm^2$ is often used by hospitals as a UVC dose target in operating rooms and patient rooms.

Surface Disinfection Considerations

A cosine-corrected UVC dosimeter can be used to determine the dose and disinfection efficacy of any surface, but this assumes a perfectly smooth surface where all pathogens are exposed to the UVC light. However, 'smooth' surfaces are actually very rough at the scale of most pathogens.

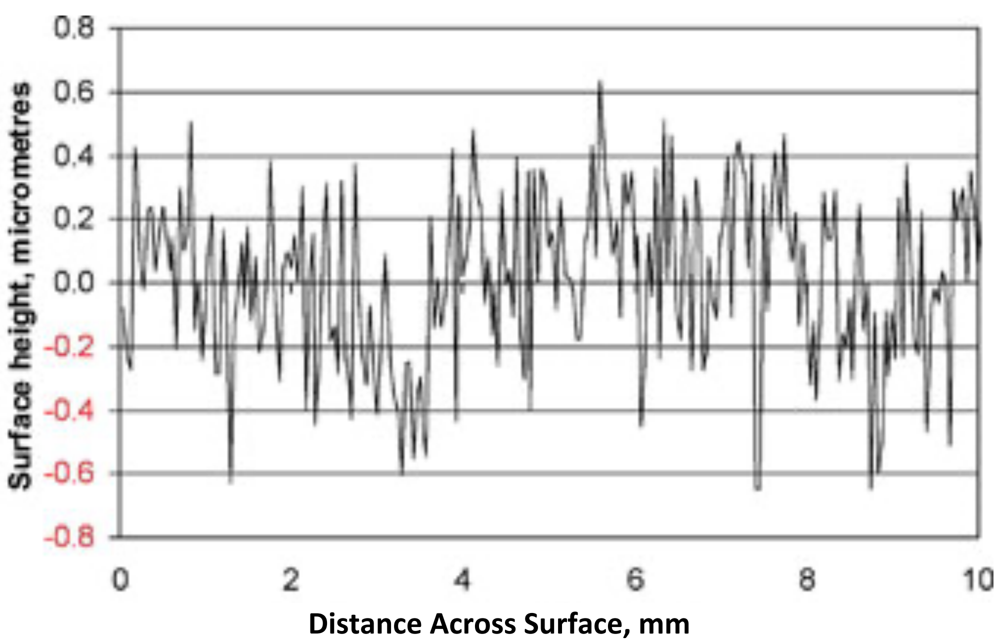
A SARS-CoV-2 virus measures approximately 100nm (0.1micrometers) – this is 700 times smaller than the thickness of a human hair! Because of its small size, the SARS-CoV-2 virus can easily hide in in the valleys of apparently smooth surfaces.

To use another analogy, it's like sunshine in the mountains. At mid-day when the sun is overhead, almost every area on the ground receives direct sunshine, but when the sun is low, many areas are shadowed by mountains. Such is the case on a microscopic scale with UVC on common surfaces.

Shown below is a close-up image of a typical wall with a medium texture, looking much like a picture of mountains from space. In this photo, shadowed areas are apparent on the southeast side of the tiny mountains. Viruses hiding in these shadowed areas will receive a tiny fraction of the normal UVC dose and will likely survive unimpaired.

Medium Wall Texture

Stainless steel, a material commonly used in medical applications, also has significant surface roughness at a microscopic scale. A no. 4 surface is common for door handles, bedrails, etc., and as shown below, has crevasses sufficiently deep to hide viruses from light at low angles.



No. 4 Stainless Steel Surface Roughness

Cosine correction accounts for power reduction due to UVC light hitting a surface at an angle, but it does <u>not</u> account for shadows. Even if a surface is disinfected with sufficient dose for an LRV4 reduction (99.99% pathogens neutralized), pathogens in shadowed areas may escape largely unaffected. As a result, if 10% of the surface area is shadowed, an LRV4 dose will result in an effective LRV of only 1 (only 90% of pathogens neutralized).

UVCense dosimeters intentionally depart from ideal cosine correction for light angles greater than ±55°. This rapidly declining sensitivity for steep angles accounts for the surface roughness of real-world surfaces. Although only an approximation, this modified cosine correction curve is believed to provide a more realistic representation of real-world disinfection efficacy in UVGI applications.

Conclusion

Wide measurement disparity can be seen when comparing power and dose measurements of various UVC meters. The predominant cause of this disparity is believed to be inaccurate cosine correction. Consequently, the only consistent method of calibrating or evaluating UVC meters is by using columnated UVC light perpendicular to the sensor.

Because real-world surfaces such as walls and stainless steel have significant roughness at microscopic levels, UVC impacting these surfaces at steep angles has reduced disinfection efficacy. Shadows that form on rough surfaces can leave a significant percentage of pathogens unaffected due to the low levels of UVC received.

References

[1] Adel Haji Malayeri, Madjid Mohseni, Bill Cairns, James R. Bolton, Gabriel Chevrefils, Eric Caron, Benoit Barbeau, Harold Wright, Karl G. Linden. Fluence (UV Dose) Required to Achieve Incremental Log Inactivation of Bacteria, Protozoa, Viruses and Algae. Department of Chemical and Biological Engineering, University of British Columbia, Vancouver, BC, Canada. https://www.iuvanews.com/stories/pdf/archives/180301_UVSensitivityReview_full.pdf