Whitepaper: Ultraviolet (UV) Irradiation for Disinfection

December 2020

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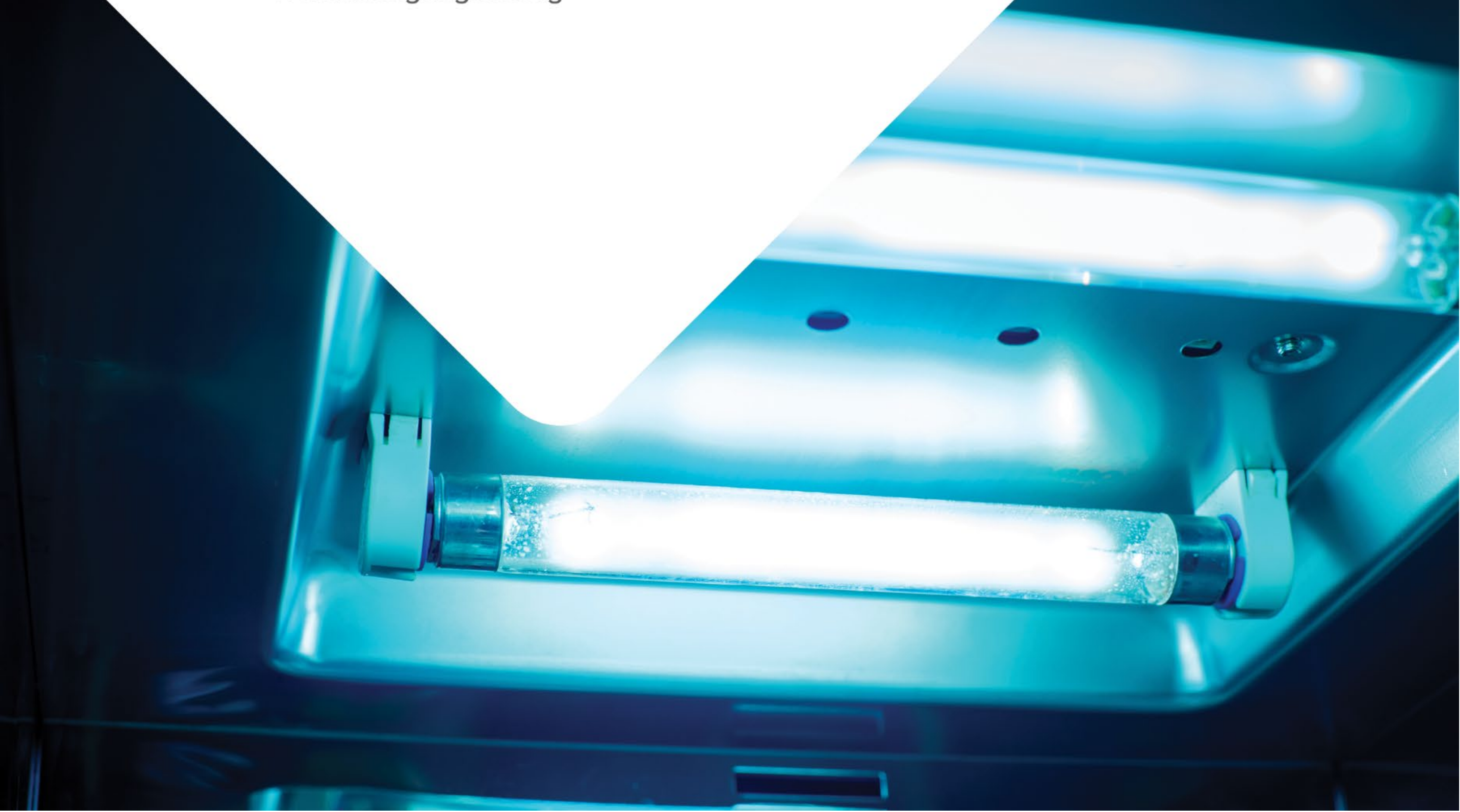

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Executive Summary

This whitepaper introduces disinfection technology with a focus on ultraviolet (UV) sources and applications, dosing for inactivation of pathogens, specification of disinfection products, safety and performance testing, and the effects of UV disinfection on people and the environment.

Naturally, there is recent interest in inactivating SARS-CoV-2, the pathogen that causes COVID-19. In lab applications, ultraviolet germicidal irradiation (UVGI) has been shown to inactivate several different strains of coronavirus, and several recent publications have demonstrated that UVGI could inactivate SARS-CoV-2. Lamps and luminaires that produce UVGI (also known as UVC or germicidal ultraviolet (GUV)) are the most effective and commonly used UV disinfection sources to inactivate viruses. UVGI devices that produce peak wavelengths of 254 nm are the most prevalent of these sources. Despite the potential of UVGI, many questions remain unanswered regarding the appropriate dose to inactivate pathogens in real world situations and the effects of different environments on effective disinfection.

Terminology:
IRRADIATION vs LIGHT

Light is defined as radiant energy that is capable of exciting the human retina and producing a visual sensation. **Irradiation** is radiant energy incident on a surface and is not weighted by the human response to light. This whitepaper will refer to UV disinfection sources as “**radiation**” or producing “**irradiation**” throughout.

Throughout this whitepaper, readers are provided with recommended questions to ask manufacturers before purchasing and installing UV lamps and luminaires in order to ensure effective disinfection and safety. This list of questions is available in full at the end of the whitepaper. The following factors (among others) must be considered:

- UVGI can be used in both occupied and unoccupied commercial, industrial, and healthcare spaces. Extreme care must be taken in product selection and use to ensure safety in occupied and unoccupied areas.
- Dose (amount of UV irradiation provided over time) and desired disinfection level (the UV’s effectiveness at inactivating the pathogen) are essential calculations, and must take into account the specific pathogen, environment, and spectrum of the UV source.
- All installed ultraviolet disinfection products should be certified for safety by a Nationally Recognized Testing Laboratory and should be tested per CIE/IEC 62471:2006, classified based on risk groups, and labeled accordingly. Depending on the technology and application, appropriate safety certification standards currently include UL1598 Annex L, UL1598 Annex M, and UL OOI 8802. There is not an Occupational and Health Administration (OSHA) standard for exposure to ultraviolet radiation.
- Although the EPA does not evaluate safety or efficacy claims, UV sources claiming to inactivate viruses and bacteria are pesticide devices and are federally regulated by the EPA. The EPA also has pesticide device labeling requirements that include warning and caution statements, directions for use, and the EPA establishment number. Compliance advisories can be found on the EPA website here and here.
- Manufacturers with verifiable performance claims should be willing to share supporting documentation with specifiers.
- Short-wavelength sources, such as 405 nm sources, may be generally impractical for effective disinfection because the dose needed to achieve moderate bacterial disinfection is exceedingly high.

Though UV disinfection technology has great potential to inactivate SARS-CoV-2 and other pathogens in a variety of situations, it is important to remember that unsafe doses of UVGI can damage the DNA of *every living organism,* and may cause damage to surfaces and materials. Safety considerations are of utmost importance when installing, commissioning, maintaining, and using UV disinfection technology, and precautions must be taken to ensure adequate systems are in place to protect people from overexposure in occupied and unoccupied spaces.

Specifiers and other lighting decision makers are encouraged to use the list of questions at the end of this whitepaper as a starting point to engage manufacturers about safe and effective use of their UV disinfection products.

Introduction

There has been interest and success in using ultraviolet (UV) radiation for disinfection for over 110 years, dating back to 1910 in Marseille, France, where UV was used to disinfect drinking water (Reed, 2010). Historically, ultraviolet radiation has been used for disinfection (to inactivate a pathogen) in a myriad of applications, notably air disinfection for tuberculosis treatment and water purification. UV radiation may also be used to control pathogens in healthcare settings, where healthcare-acquired infections (HAIs) kill almost 100,000 people annually (Baker, 2020).

In lab applications, some wavelengths of UV have been shown to inactivate several different strains of coronavirus, and recent laboratory testing has demonstrated that some applications of UV inactivate SARS-CoV-2, the pathogen causing COVID-19. Though much research is being performed, many questions remain unanswered regarding the dose needed to inactivate pathogens in real world situations. Some progress is being made with regards to standards for UV performance testing (Baker, 2020), but standardization for consumer and workplace safety, dosing, and effective disinfection is currently lacking. Organizations like ASHRAE and IES are developing new guidelines and recommended practices for performing UV disinfection safely and effectively.

This whitepaper introduces UV disinfection with a focus on UV sources and applications, adequate dosing for inactivation of pathogens, specification of UV disinfection products, safety and performance testing, and the effects of UV disinfection technologies on people and the environment. Readers are provided with a set of recommended questions to ask manufacturers before purchasing UV disinfection products, and names of and links to technical resources for further reading.

Citations are provided for several peer-reviewed publications, books, governmental reports, and product databases that were used to gather information for this whitepaper. Some of these publications are also listed as technical resources if they provide additional design, safety, or performance guidance to the reader.

What is ultraviolet radiation?

Ultraviolet (UV) radiation covers wavelengths from 100 nm – 400 nm. It is broken into three ranges: (CIE, 2003):

- UVC (100 – 280 nm)
- UVB (280 – 315 nm)
- UVA (315 – 400 nm)

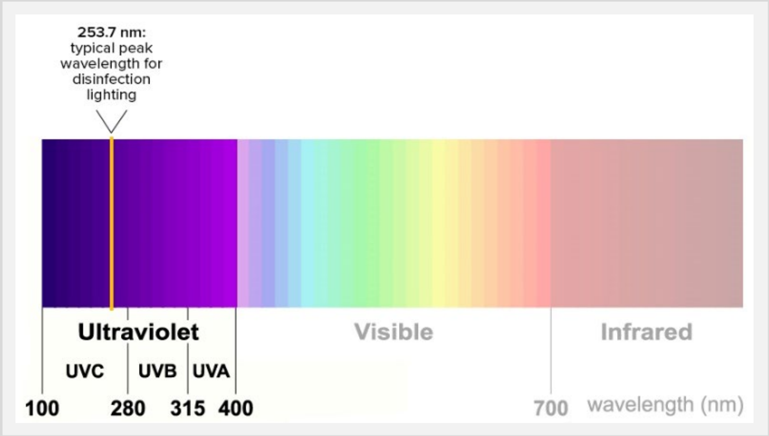

Figure 1: The ultraviolet spectrum.

UVC/ULTRAVIOLET GERMICIDAL IRRADIATION

Lamps and luminaires that produce **ultraviolet germicidal irradiation** (UVGI, also called UVC or germicidal ultraviolet (GUV)) are the most effective and commonly used UV devices to inactivate pathogens. The most common UVGI luminaires use low pressure mercury lamps and have a peak wavelength of 253.7 nm (nominally stated as 254 nm), but UV sources between 220 and 313 nm can also have a germicidal effect. In all cases, effectiveness depends on the specific pathogen, wavelength generated, and dose (CIE, 2003; IES, 2011).

UVGI in the 200 – 280 nm range causes damage to the DNA and RNA of all pathogens, including bacteria, molds, viruses, and yeasts, which results in their inactivation under the right conditions[1]. It is important to note that UVGI may also produce mutations in the DNA and RNA of all living tissues, including those of humans, animals, and plants. **This whitepaper will primarily focus on the germicidal effects of UVGI wavelengths.**

UVA AND SHORT WAVELENGTH (e.g. 405 nm) IRRADIATION

UVA and short wavelength visible radiation with a peak wavelength of 405 nm can also have a germicidal effect on some bacteria, molds, and yeasts by producing oxidative damage within the microorganism. As with UVGI, the damage is dependent on the pathogen, wavelengths, and dose. 405 nm sources can be effective at inactivating some bacteria at very high doses. **However, these technologies have not demonstrated effectiveness against most viruses,** and are less effective than UVGI at inactivating bacteria and molds. Therefore, they are not the focus of this whitepaper.

MEASURING UV DISINFECTION IRRADIATION

Because the output of UV disinfection sources is typically described in units of radiant power (milli (m)W or W rather than lumens), lumens per watt (LPW), or efficacy, is not used to characterize UV sources. Rather, **efficiency** (unitless) is used to describe the ratio of radiant power divided by input power. All output, efficiency, and life data described in the below Q&As is rated (nominal) data for lamps and/or UV products[2] and does not reflect luminaire or application losses. **Source efficiency should not be confused with disinfection effectiveness.** A disinfection source may be very efficient at producing UVGI, but may not be an effective disinfectant if the dose and disinfection level are not sufficient to inactivate the target pathogens.

How is the effectiveness of UV disinfection irradiation measured?

Two factors are essential to consider when selecting UV disinfection products in order to ensure effective inactivation of pathogens: the **dose** from the disinfection product and the **disinfection level**.

The **dose**[3] from the disinfection product is the amount of UV irradiance incident upon a unit area of a target surface (typically given in mW/cm^2 or W/m^2), multiplied by the amount of time the UV irradiance is applied to the target surface or area. It is measured in millijoules per square centimeter (mJ/cm^2) or

[1] Some bacterial pathogens, like certain strains of E. coli, have a photo repair mechanism, which is activated by high doses of UVA and short wavelength radiation (330 – 480 nm). This mechanism, called photoreactivation, repairs the DNA damage caused by the UVGI treatment if the supplemental radiation is present at the same time or shortly after the UVGI treatment is given. (CIE, 2003; Kowalski, 2009)

[2] Performance data for UV disinfection products includes the following technologies: Chip, Chip on Board (COB), Surface-mounted Diode (CMD), T-Type, and Package on Board (POB) from Kopp Glass UV LED Product Database as of June 2020.

[3] Dose (J/m^2) = irradiance (W/m^2) x time (seconds). Other units of irradiance or dose may be shown (e.g. mJ/cm^2, uJ/cm^2, mW/cm^2, J/cm^2, etc.) but it is preferred that the irradiance and dose have the same unit prefix (e.g. milli or micro).

Joules per square meter (J/m^2). Dose can be thought of as the total amount of germicidally-active irradiation over time.

The **disinfection level** indicates how effective the disinfection dose is for inactivating the pathogen. Disinfection level can be described in one of two ways:

- **Percentage of inactivated pathogens:** In this method, the percentage of pathogens inactivated (or killed) by the dose of disinfection irradiation is specified. For example, a D_{90} disinfection rate specifies that 90% of the pathogens are inactivated by the given dose.
- **Log Inactivation of pathogens:** This method specifies the logarithmic reduction of pathogens after a specific dose of disinfection irradiation is applied. This percentage is known as "Log_{10} Inactivation" or sometimes stated as "Log Kill". Log Inactivation is calculated by taking the common logarithm of the surviving fraction of pathogens.[4] For example, a given dose that allows 10% of the pathogens to survive (e.g. a D_{90} rate) is presented as a Log Inactivation of 1 ($\log_{10}(0.1)=-1$, or a 1-$\log_{10}$ reduction). It is up to the specifier to indicate the desired disinfection level, keeping in mind that this model to predict deactivation by irradiation is exponential, and that each subsequent increase in Log Inactivation requires the same multiple increase in dose. For example, to increase the Log Inactivation from 1 (D_{90}) to 4 ($D_{99.99}$), one would have to quadruple the disinfection radiation dose.[5]

The target dose needed for disinfection depends on the pathogen, the desired disinfection level (i.e. the desired percentage of pathogens inactivated), the pathogen location (on surfaces, aerosolized in air, or in liquid droplets), what might be on the surface of the pathogen, and the spectrum of the disinfection source.[6] Malayeri et al (2016) and Kowalski (2009) provide tables of UVGI Log Inactivation for various viruses, bacteria, algae and mold spores.

Published disinfection rates and doses for many pathogens are usually based on low pressure or medium pressure UVGI lamps, mostly focusing on the effect of 254 nm (Malayeri, Mohseni, Cairns, & Bolton, 2016). However, there is emerging peer-reviewed literature about the impact of 222 nm excimer lamps on SARS-CoV-2, as well as on other strains of coronavirus (Buonanno, Welch, Shuryak, & Brenner, 2020; Kitagawa, et al., 2020).

What are the potential applications of disinfection irradiation?

Disinfection sources can be used to target pathogens in air, liquid, or on surfaces.[7] No matter the application, it is vital to choose lamps and luminaires based on the pathogen, the desired disinfection

[4] Another way to think about the disinfection level is as a ratio of remaining pathogens. For example, if the initial number of microorganisms was 10^6, and the remaining number after disinfection was 10^5, then the ratio is 10. The $\log_{10}$ of 10 is 1. If the initial number of microorganisms was 10^6, and the remaining number after disinfection was 10^4, then the ratio is 100. The $\log_{10}$ of 100 is 2.

[5] Note that although the exponential model is widely accepted, it can overestimate the Log Inactivation in some situations.

[6] Each pathogen (and strain) has its own decay constant which specifies how resistant it is to UVGI or other wavelengths of radiation, meaning different pathogens will need to be exposed to a disinfection source for differing lengths of time to be inactivated.

[7] Liquid treatment, such as water purification, is not discussed in detail in this whitepaper. Please see the following resource for an example of suggested guidelines for water purification: https://7d22a3c6-d58b-4636-8cac-3260dc7d6552.filesusr.com/ugd/632dc3_c8ab78b05021452c8a520c3b6dba48ca.pdf?index=true

level, the source and pathogen location, and the spectrum of the UV disinfection source to achieve the desired results.

USING UV DISINFECTION IRRADIATION TO INACTIVATE SARS-CoV-2

Naturally, there is great interest in using UV disinfection to inactivate SARS-CoV-2, the pathogen that causes COVID-19. Published peer-reviewed literature exists for using UVGI to inactivate other coronaviruses, and it is likely that the dose needed to achieve effective inactivation of SARS-CoV-2 will be similar (between 8 – 3000 mJ/cm^2 depending on the target disinfection level) (International Ultraviolet Association (IUVA), 2020). One recent paper (Heilingloh, et al., 2020) shows that a high dose of UVGI (1048 mJ/cm^2) inactivated 99.9999% of SARS-CoV-2 in a highly concentrated viral solution[8], while other recent papers (Patterson, et al., 2020; Inagaki, Saito, Sugiyama, Okabayashi, & Fujimoto, 2020) showed that much lower doses (about 40 mJ/cm^2 or higher) of UVGI (254 nm and 280 nm, respectively) inactivated SARS-CoV-2 by 99.9999% and 99.9%, respectively, in a highly concentrated viral solution. Kitagawa et al. (2020) demonstrated that a 3 mJ/cm^2 dose of 222 nm UVGI with a bandpass filter inactivated dried SARS-CoV-2 viral cells by 99.7%.[9] See **Table 1** for a summary.

Table 1. UVGI doses that inactivate SARS-CoV-2 virus based on a selection of recent publications

Publication	UVGI Dose	Peak Wavelength	Media	Disinfection level
Heilingloh et al. 2020	1048 mJ/cm^2 [10]	254 nm	Highly concentrated viral solution	99.9999%
Patterson et al. 2020	40 mJ/cm^2	254 nm	Highly concentrated viral solution	99.9999%
Inagaki et al. 2020	37.5 mJ/cm^2	280 nm	Highly concentrated viral solution	99.9%
Kitagawa et al. 2020	3 mJ/cm^2	222 nm with a bandpass filter	Dried viral cells	99.7%

USING UV DISINFECTION IRRADIATION TO INACTIVATE OTHER PATHOGENS

Published peer-reviewed research and textbook reference UVGI dose-response data, usually with a 254 nm peak, is also available for many other pathogens that cause illness, such as influenza A, *Staphylococcus aurus* (Staph), methicillin-resistant *Staphylococcus aurus* (MRSA), *Escherichia coli* (*E. coli*), and others (Malayeri, Mohseni, Cairns, & Bolton, 2016; Kowalski, 2009). It is important to note that each pathogen has its own sensitivity to UVGI, which is also dependent on the disinfection source spectrum and the pathogen location (in air, in media, or dried on a surface).[11]

Some bacterial pathogens (e.g. Staph, MRSA, *E.coli*) can be inactivated by UVA sources with a peak wavelength of 365 nm, but the doses required to achieve effective disinfection are tens or hundreds of

[8] A dose this high in application may be harmful to humans.

[9] Only peer -reviewed publications are included in this summary. It is reasonable to expect that more peer-reviewed research using UVGI on SARS-CoV-2 will continue to be published in the near term, based on publicly available pre-peer review pre-prints.

[10] A dose this high in application may be harmful to humans.

[11] Aerosols and media absorb UVGI in a spectrally dependent manner and thereby reduce the transmission to the pathogen. Other variables also affect dose response, leading to potentially large variability for the same pathogen (review here: https://www.nist.gov/document/john-boycerequired-doses)

times higher than the doses needed if UVGI sources are used. (Livingston, Cadnum, Benner, & Donskey, 2020; Brons, et al., 2020). UVA sources are ineffective in inactivating most viruses, unless an external photosensitizer[12] is present, and are therefore not the focus of this whitepaper.

Short wavelength (e.g. 405 nm) sources can also inactivate some bacterial and fungal pathogens (e.g. Staph, *E. coli*, *L. monocytogenes*, *Salmonella enterica*); however, effective disinfection may require doses thousands of times higher than UVGI (upwards of 300,000 J/m^2 (Murdoch, Maclean, Endarko, MacGregor, & Anderson, 2012), making its effective use generally impractical. Viruses without internal or external photosensitizers are not generally able to be inactivated with 405 nm (or UVA) sources (Karlicek, 2020). **Short wavelength sources are generally impractical for effective disinfection.**

Questions to ask before purchasing and installing:

- What are the wavelengths used in the product for disinfection? Specifiers should ask for a spectral power distribution (SPD), or an image of the SPD.
- What pathogens are specifically targeted by the product and what is the target dose and disinfection level for each? Is there peer-reviewed research or laboratory testing supporting the claims?

How is UV disinfection used in commercial, industrial, and healthcare spaces?

UVGI can be used in both occupied and unoccupied commercial, industrial, and healthcare spaces. Extreme care must be taken to ensure safety when used in occupied and unoccupied areas.

- **HVAC systems**
  UVGI can be safely installed in air handlers and/or ventilation ducts of commercial, industrial, and healthcare spaces, as humans do not occupy these areas. These systems are typically installed to clean coils and drip pans or disinfect the air, and typically utilize 254 nm low pressure mercury lamps. Newer broadband pulsed xenon technology is also an option. Appropriate precautions to view and switch off the UV lamps and luminaires must be taken when installers or maintenance staff are working with the HVAC system when required by the wavelength technology in use. Potential photodegradation of duct linings and internal wiring must be considered in the design of these systems. *ASHRAE Standard 185.1-2020 provides the test method for UVGI sources for use in air-handling units or air ducts to inactivate airborne microorganisms, while ASHRAE Standard 185.2-2020 provides the test method for UVGI sources for use in air-handling units or air ducts to inactivate microorganisms on irradiated surfaces.*

[12] Photosensitizers are molecules that are activated by light. If external photosensitizers are present with viruses, they may be activated by UVA or 405 nm radiation. See for example: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4116386/

- **Occupied spaces**
  In commercial, industrial, and healthcare settings[13], 254 nm UVGI products can be installed in the upper room zones of occupied spaces as long as luminaires are mounted at least 2.1 m (6.9 ft) above the floor and the exposure level to occupants is at or below levels permitted by CIE/IEC 62471. In the case of installations in upper room zones, adequate shielding (such as louvers or baffles) to reduce exposure to occupants in the lower portion of the room may be required (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2014 (Reaffirmed 2020)).[14]

  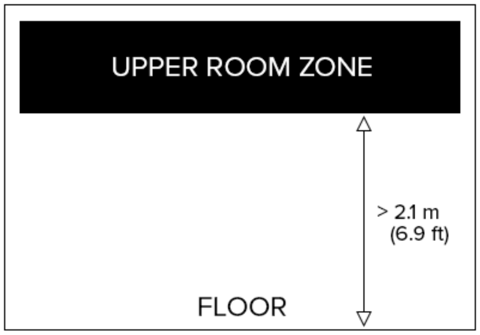

  Figure 2: Upper room zone.

  Other UVGI technologies may also be safely installed and operated in occupied spaces as long as the product meets required CIE/IEC 62471 safety thresholds. *UL 1598 Annex L addresses permanently mounted germicidal equipment intended for occupied spaces and is geared towards upper room applications. UL 1598 Annex M covers UV emitter assemblies that will be included in a commercial product.*

- **Unoccupied spaces**
  As noted above, UVGI products can be installed in air handlers and/or ventilation ducts. In addition, mobile 254 nm UVGI devices or ceiling-mounted/pendant luminaires with a downward distribution may be installed and used in unoccupied spaces if adequate safety measures are taken so that these products turn off when occupants enter the space. *UL 8802 addresses permanently mounted germicidal equipment that is dependent on safety controls to limit exposure, as may occur in unoccupied spaces.*

UVGI air treatment in air handlers and/or ducts can be classified by dose ranges using a UVGI Rating Value Scale (URV) (Kowalski, 2009). The URV rating system is intended to be used as a comparison system to Minimum Efficiency Reporting Values (MERV) ratings, which specify an air filter's efficiency at trapping particles between 0.3 and 10 microns.[15] A UVGI system with a URV of 13 (producing a dose of 20 – 29.99 J/m^2) would provide similar filtration to a MERV 13 filter (International Ultraviolet Association (IUVA), 2005). URV categories range from 1 (0.01 J/m^2) to 20 (200 J/m^2).[16] UVGI design considerations for HVAC or upper room applications are beyond the scope of this whitepaper; readers are directed to relevant ASHRAE, CDC/NIOSH, and IUVA guides in the References section.

Target dose is distance dependent, and specifiers should confirm the average irradiance, uniformity ratios, and target doses at relevant distances from the UV device. Many architectural surfaces are poor reflectors of UVGI (Philips Lighting B.V., 2006) and/or UVA; although plaster and aluminum may reflect 40 – 90% of 254 nm radiation. Surface reflectances should be accurately assessed to predict and measure the delivered dose. Shadowed and/or dirty surfaces may not receive sufficient doses to meet

[13] Strategies vary per occupancy category. See the referenced ASHRAE Position Statement for details. Criteria for ventilation design for healthcare facilities are provided in ANSI/ASHRAE/ASHE Standard 170-2008.
[14] UVGI should be deployed as an adjunct intervention, not a standalone intervention. Traditional cleaning and disinfection practices as well as adequate ventilation should also be employed. See for example: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7115255/
[15] https://www.epa.gov/indoor-air-quality-iaq/what-merv-rating-1
[16] ASHRAE suggests that some HVAC actions may reduce the spread of SARS-CoV-2, including the use of MERV 13 filtration. https://www.ashrae.org/news/ashraejournal/guidance-for-building-operations-during-the-covid-19-pandemic

the target disinfection levels. Mobile devices[17] may need to be safely moved around, or moved autonomously, to provide the target dose to all surfaces of interest, or UV-reflective coatings may be applied to room surfaces to increase disinfection efficacy.[18]

Controls and sensors are of utmost importance to UV disinfection systems that are not designed for continuously occupied spaces. When UV disinfection is designed for unoccupied spaces, sensors should be employed to turn off the sources when occupancy is detected. A single occupancy sensor may not be enough to detect the presence of people; rather a system of sensors and controls may be needed (Global Lighting Association, 2020). For upper room UVGI, sensors and/or controls can be used to switch off the luminaires when the space is unoccupied or when the facility is closed; however, to ensure that the target disinfection level is met, consult with the device manufacturer to determine if a time delay is needed before turning luminaires off. Similarly, in air handling units and/or ducts, the UVGI system can be interlocked with the fan so that the lamps are off when the fan is off to save energy and potentially prolong lamp life.

UVA and short-wavelength disinfection systems are also marketed for commercial and healthcare environments and are currently available in form factors ranging from troffers to surface-mounted panels to downlights, usually with a white UVA LED channel. However, because UVA is not effective for inactivating most viruses, including SARS-CoV-2, (and is less effective at inactivating bacterial pathogens than UVGI), and because short-wavelength products (e.g. 405 nm) are impractical for general disinfection use because of the extremely high dose needed to achieve modest bacterial inactivation, this paper will not go into detail on these sources.

Questions to ask before purchasing and installing:

- How is the product used in application (continuous use, on until target dose is achieved, etc.)?
- How many hours per use/day/year will be needed?
- For surface disinfection, what is the effective distance at which the target dose is given, and what is the irradiance at that distance?
- How is the system installed and commissioned to ensure the target dose is achieved?
- What are the safety features and considerations of the product? Does it need to be installed with other sensors or controls to be used safely? What are the performance specifications on the controls and sensors?

What commercial UV sources provide effective disinfection?

Currently, the most common and cost-effective sources for UVGI are low pressure and medium pressure mercury lamps. Low pressure mercury lamps are typically used for air and surface disinfection, whereas medium pressure mercury lamps are used for water purification (Bergman, 2020). Excimer lamps with krypton-chloride gas fill and UVC LEDs are also available for disinfection of pathogens. A recent Global Lighting Association (GLA) paper contains additional information about these and other sources for disinfection (Global Lighting Association, 2020).

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[17] Examples of mobile devices: https://www.purplesun.com, https://cleanlightmedical.com/uv-trolley, http://news.mit.edu/2020/csail-robot-disinfects-greater-boston-food-bank-covid-19-0629

[18] See for example: https://www.cambridge.org/core/journals/infection-control-and-hospital-epidemiology/article/rapid-hospital-room-decontamination-using-ultraviolet-uv-light-with-a-nanostructured-uvreflective-wall-coating/50AA77C3A0B7758550BC15DC661B30FA

Importantly, IUVA cautions buyers to beware, as there are currently "few accepted standards" to determine the performance of UVGI devices (International Ultraviolet Association (IUVA), 2020).

UV technologies that claim to prevent, destroy, or mitigate pathogens such as viruses, bacteria, or other microorganisms by physical means (such as irradiation) rather than by chemical means are federally regulated by the EPA as pesticide devices (United States Environmental Protection Agency (EPA), 2020). Pesticide devices do not need to be registered by the EPA, but the devices must be produced in EPA-registered establishments and specifiers should check that the companies producing these devices are listed in the EPA's database.[19]

The EPA also has pesticide device labeling requirements that include warning and caution statements, directions for use, and the EPA establishment number. The EPA does not routinely confirm the safety or efficacy of UV devices; however, they do require that all claims be true and not misleading. It is also important to note that several U.S. states have various regulation and registration requirements for UV disinfection sources.[20]

405 nm products are not mentioned in this section because, as previously noted, their use is generally impractical for effective disinfection. Additionally, devices that produce ozone above acceptable ozone exposure limits should be avoided because they pose an additional safety hazard. See the GLA Position Statement on UVC Safety Guidelines (Global Lighting Association, 2020) for additional information on ozone exposure limits.

LOW PRESSURE UVC MERCURY LAMPS

Low pressure UVC mercury lamps, historically the primary choice for air and surface disinfection, produce a series of emission lines with a primary peak at 253.7 nm, and much smaller emission lines around 280, 297, 303, 313, 400, 405, and 436 nm (ICNIRP (The International Commission on Non-Ionizing Radiation Protection, 2004; Bergman, 2020).

- Linear lamps are about 30% efficient at converting electric power to radiant power between 200 and 280 nm, with rated efficiency varying with lamp shape, length and power.[21]
- The average rated radiant UVGI power is about 9W, ranging from 0.8 – 27 W.
- In application, efficiency is also dependent on the bulb wall temperature and air velocity or wind chill factor (Bahnfleth, 2020; Philips Lighting B.V., 2006).
- Luminaires that incorporate additional optics to control the distribution, such as louvers, can reduce the light output by 25 – 50% or even as much as 99% (Krames, 2020; National Institute for Occupational Safety and Health (NIOSH), 2009).
- Rated life is typically around 9000 hours and determined as a function of switching frequency, ambient temperature, lamp current, and lamp design (Philips Lighting B.V., 2006).
- Darkening of the bulb envelope results in optical power depreciation (Bergman, 2020).

Low pressure UVC mercury lamps typically have a specific type of glass bulb that blocks emission below 200 – 220 nm so that dangerous ozone gas is not generated (Bergman, 2020), but this may differ from manufacturer to manufacturer so specifiers should ask if all ozone-producing radiation is blocked by the bulb.[22]

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[19] https://www.epa.gov/compliance/national-list-active-epa-registered-foreign-and-domestic-pesticide-andor-device-producing

[20] http://npic.orst.edu/reg/state_agencies.html

[21] Based on an analysis of major UVGI lamp manufacturer spec sheets in July 2020.

[22] Specifiers are advised to ask about the spectral transmission of the envelope and the amount of ozone produced.

MEDIUM PRESSURE UVC MERCURY LAMPS

Medium pressure UVC mercury lamps are not covered in detail here because they are typically used for water purification. In general, they produce a broader spectral power distribution in the UVC range and UVB range than low pressure, and produce much higher radiant output, including large increases in UVB (Bergman, 2020). UVC efficiency is only 15% or lower, but the amount of UVC is increased relative to low pressure UVC mercury lamps, such that the optical power density may be as high as 100 W per inch (Bergman, 2020).

EXCIMER UVC LAMPS WITH KRYPTON-CHLORIDE GAS FILL

Excimer lamps with a krypton-chloride (KrCl) gas fill are becoming commercially available for disinfection (e.g. Ushio Care222 modules[23]), but information on efficiency and rated life was generally not found.[24] These lamps produce a narrowband peak wavelength at 222 nm, and much smaller emissions between 225 – 260 nm (Buananno, et al., 2017). A high quality short bandpass filter should be added to exclude UVC emissions above 230 nm to make the light safer for occupants. Specifiers should also ask about ozone production.

UVC LEDs

UVC LEDs with peak emission wavelengths between 235 – 280 nm are also available for disinfection purposes.

- Median radiant output is typically between 1 – 12 mW, although many UVC LEDs have radiant output around 0.05 mW, and some LED products can have radiant outputs as high as 200 mW at 280 nm (Kopp Glass, 2020).
- UVC LED efficiency is typically between 1 – 6% in the 265 – 280 nm range (Karlicek, 2020; Kopp Glass, 2020; Krames, 2020) and decreases with shorter wavelengths.
- L_{70} is typically between 5,000 – 10,000 hours (Karlicek, 2020).

PULSED XENON ARC LAMPS

Pulsed xenon arc lamps are high-powered arc lamps (generally containing xenon gas) that produce rapid pulses of intense energy.

- These lamps emit a broad band of visible and UV wavelengths from approximately 200 nm – 1000 nm, with a significant fraction in the UVC band. Some pulsed xenon lamps are filtered so that they only emit UV.
- Pulsed xenon lamps may have higher power demand than other UVC technologies.
- These lamps inactivate pathogens using the same mechanisms as other UVGI technologies.

Questions to ask before purchasing and installing disinfection products of any wavelength:

- What is the optical power (in W or mW) of the product? If the product being evaluated is a luminaire, the luminaire output should be given accounting for all optics (not just lamp output).
- What is the input power and efficiency (optical power/input power) of the product?
- What is the rated life of the product and how is it calculated (e.g. L_{70}, B_{50} (failure rate at which 50% of a large sample fail), etc.))?
- What is the optical power depreciation of the product over the rated life?

[23] https://www.ushio.eu/excimer-explained/

[24] One manufacturer claims a 2000 – 6000 hour life for their product (https://edenpark.com). Another manufacturer claims a 3000-hour rated life using L_{70}.

- Does the product produce ozone in the application? This may be a bigger issue for small spaces where products are operating continuously (like air-handlers or small rooms).

What are the safety considerations of using UV disinfection?

In unoccupied spaces, UVGI can be safely installed, commissioned, and maintained if adequate precautions and trainings are followed and sufficient measures are taken to protect potential occupants from overexposure. In occupied spaces, UVGI products can be installed when the exposure level to occupants is at or below levels permitted by CIE/IEC 62471. GLA recommends that devices with a UVC Risk Group classification of 1 or higher have instructional safeguards and are only accessible to Skilled Persons employing PPE (Global Lighting Association, 2020).

It is important to remember that unsafe levels of UVGI can damage the DNA of *every living organism,* including children, pets, and plants. UVGI is absorbed by the outer layers of skin and corneas. Exposures at high enough doses can cause temporary skin irritation (erythema (e.g. sunburn)) and eye irritation (redness, blurred vision, tearing, light sensitivity (e.g. photokeratitis and conjunctivitis)) (Bahnfleth, 2020). Symptoms develop 4 – 12 hours after exposure and may last up to 48 hours. (Bahnfleth, 2020). Because the uncomfortable, even painful, effects of overdose aren't experienced until many hours later, occupants who have been exposed to UVGI may not even realize why they are experiencing these reactions. Incidental exposure to UVGI does not increase the lifetime risk of cataracts or skin cancer because UVC wavelengths only penetrate the superficial layers of the skin and eyes (Illuminating Engineering Society (IES) , 2020).

Houseplants, especially ones suited for low light levels, will show leaf browning, growth reduction, and eventually death under prolonged UVGI, even at threshold levels shown to be safe to human eyes and skin (Kowalski, 2009). Plants should be removed from spaces during the times UVGI will be directed towards them.[25]

SAFETY CERTIFICATION FOR UV DISINFECTION

At minimum, all installed lamps and luminaires should be tested to the relevant safety standard (e.g. UL 1598 for luminaires) by an appropriately accredited Nationally Recognized Testing Laboratory (NRTL) or safety certification laboratory. The testing standards from standards developing organizations (SDO) listed below specify additional measurement and threshold requirements, risk group classifications, and labeling requirements for safe use of disinfection sources.

- **CIE/IEC 62471:2006 (CIE S 009:2002)** Photobiological safety of lamps and lamp systems.
- **IES RP-27.1-15** Recommended Practice for Photobiological Safety for Lamps – Measurement Techniques.
- **IES RP-27.2-00** Recommended Practice for Photobiological Safety for Lamps – General Requirements.
- **IES RP-27.3-17** Recommended Practice for Photobiological Safety for Lamps – Risk Group Classification and Labeling.
- **UL SAFETY STANDARDS:** Several UL standards have recently added proposed certification guidance for UVGI products and systems (e.g. UL 1598 Annex L or M and UL 8802 Outline of Investigation (OOI) for Germicidal Systems). This work is expected to continue.

[25] Plants may not show deleterious effects under UVA, especially if UVA levels are lower than sunlight.

Safety certification laboratories will issue safety certifications based on the spectrum, type of device, and environment it will be used in (e.g. commercial, healthcare, etc.).[26] Every UVGI, UVB, UVA and 405 nm lamp and luminaire should also be tested per CIE/IEC 62471:2006, classified based on risk groups, and labeled accordingly. Products certified to UL1598 Annex L, UL1598 Annex M, or UL8802 will include testing per CIE/IEC 62471:2006.

- **UVGI (UVC) and UVB** lamps and luminaires must be measured for actinic UV hazard exposure limits for skin and eyes.
- **UVA** lamps and luminaires must be measured for actinic and near-UV hazard exposure limits for the skin and eye.
- **Short wavelength (e.g. 405 nm)** lamps and luminaires must be measured for retinal blue light hazard exposure limits.

Specifiers should understand if the luminaire's safety certification specifies the performance at a fixed distance (e.g. 200 mm away from the luminaire), and the risk group assignment and labeling requirements.

Recently, UL has published Certification Requirements Decisions (CRDs) for UL 1598, which address permanently mounted germicidal equipment for non-residential locations (Annex L) and permanently mounted UV emitter assemblies, switches, sensors, and other controls (Annex M). They have also recently published an Outline of Investigation for Germicidal Systems (UL 8802) to be used in conjunction with UL 1598.[27]

The Global Lighting Association has also released a position statement (Global Lighting Association, 2020) addressing UVGI safety requirements, while SDOs are developing their own UVGI standards. One notable recommendation is a requirement that UVC devices with a Risk Group rating of 1 or higher should have Instructional Safeguards as well as Time Safeguards to limit exposure times per the Risk Group requirements or Containment Safeguards to reduce the effective irradiation to less than 1 mW/m^2.

Although the EPA does not evaluate safety or efficacy claims, under the Federal Insecticide, Fungicide and Rodentcide Act (FIRFA), UV lights claiming to inactivate viruses and bacteria are pesticide devices and are federally regulated by the EPA. These products must be labeled per federal regulations at 40 C.F.R Part 156 (United States Environmental Protection Agency (EPA), 2020).

ESSENTIAL SAFETY PRECAUTIONS DURING INSTALLATION, COMMISSIONING, AND MAINTENANCE OF UV DISINFECTION PRODUCTS

In addition to procuring safety certification, the safety measures listed below should always be followed to ensure safe installation, commissioning, and maintenance of UVGI sources:

- UVGI devices should be installed, commissioned, and operated per manufacturers' instructions.
- UV sources should be switched off before replacement.
- Technicians should wear personal protective equipment (PPE).
- Warning signs should be posted at access points of spaces that are actively being disinfected, if required.
- In unoccupied spaces, disconnects that switch off the UVGI luminaires if occupancy is detected should be installed, if required.

[26] See for example: https://www.ul.com/offerings/ultraviolet-uvc-light-testing-and-certification
[27] https://www.shopulstandards.com/ProductDetail.aspx?productId=UL8802_1_O_20200901

- Warning labels should be clearly visible on UVGI devices (see the GLA (2020) Position Statement for examples of warning labels).

MAXIMUM RECOMMENDED DAILY EXPOSURE TO UVGI FOR HUMANS

The American Conference of Governmental Industrial Hygienists (ACGIH) publishes recommended maximum threshold limit values (TLVs) for human UV and blue-light exposure in their *Threshold Limit Values for Chemical Substances and Physical Agents & Biological Exposure Indices.*[28]

- For broadband UV sources (bandwidth > 10 nm), the maximum 24-hour wavelength-weighted dose is 30 J/m^2 (actinic weighted).
- For narrowband UV sources (bandwidth ≤ 10 nm), the maximum 24-hour dose depends on the peak wavelength of the UV source (60 J/m^2 for 254 nm narrowband sources, 220 J/m^2 for filtered 222 nm sources), with the smallest maximum dose occurring at 270 nm.

The ACGIH guidelines for TLVs are intended for occupational exposures and are application dependent. Consult with a certified industrial hygienist for guidance in making UVGI measurements to assess occupational exposures and to confirm that workers are not overexposed to UV.

NIOSH's guidelines for upper-air UVGI for tuberculosis control in healthcare settings (National Institute for Occupational Safety and Health (NIOSH), 2009) specify a maximum recommended exposure of 60 J/m^2 with a 254 nm light source.[29] For exposure times of eight hours, this equates to an average irradiance of 0.2 µW/cm^2. NIOSH recommends that multiple UVGI measurements be taken at eye level[30] in the lower room when the system is installed, when lamps are replaced, and when surfaces are repainted or recovered, and that logbooks should be maintained with this information in order to ensure that human exposure thresholds are never crossed. For direct view and UV wavelengths other than 254 nm, similar principles apply, and adjustments should be made so that the ACGIH TLVs are met for other spectra or different irradiances.

Questions to ask before purchasing and installing:

- What safety certifications are provided for the products?
- How will the installed system be commissioned, and its disinfection level evaluated?
- How will the safety of the installed system be assessed?
- How is the system maintained and what indications are provided when lamp or luminaire replacement is needed?

Does UVGI damage materials?

UVGI can cause photodamage (discoloration and degradation) to materials that absorb UV. Materials that have high UVGI reflectivity (e.g. aluminum) or high transmittivity (e.g. quartz glass) are not photodamaged by UVGI because very little is absorbed. Organic materials like wood and fiber will become discolored (bleached, yellowed or may turn brownish) by UVGI, as are paints, polyurethane foams, plastics (polymers), polycarbonate, and many types of glass (Kowalski, 2009).

Materials may lose their flexibility and/or elasticity, glues may lose their adhesive characteristics, and many plastics deteriorate under UVGI depending on the total dose and length of exposure (Kowalski,

[28] https://www.acgih.org/forms/store/ProductFormPublic/2020-tlvs-and-beis
[29] ACGIH has the same maximum dosage for this narrowband wavelength.
[30] Eye level should be based on location of occupants doing typical task work (either sitting or standing).

2009). Organic material such as electrical insulation, elastomers and sealants, filter media, gaskets and pipe insulation, and furnishings and finishes can be photodegraded by UVGI (Bahnfleth, 2020). Photodegradation may affect life and necessitate early replacement of these materials. It is unknown whether UVGI or UVA will negatively affect the performance or life of germicidal finishes, as nothing was found in peer-reviewed literature or trade publications.[31]

UV-resistant materials should be selected whenever possible and shielding of other organic materials may need to be considered.

What are the standards used for UV disinfection measurement and application?

Performing radiometric testing on UV devices requires different instrumentation than used to measure visible light, and not all test labs have the appropriate instrumentation or specialty-coated spheres to conduct these types of tests. Test methods and accuracy may vary from lab to lab as a result. Currently, there aren't any IES standards specifying how to test UVGI products. Recently, IES and IUVA signed a joint MOU to co-develop multiple standards for UGVI measurements and the first two standards are targeted for release in early 2021 (Baker, 2020). For UV equipment used in air-handling units, reference *ASHRAE Standard 185.1-2020 (Method of Testing UVC Lights for Use in Air-Handling Units or Air Ducts to Inactivate Airborne Microorganisms) and ASHRAE Standard 185.2-2020 (Method of Testing Ultraviolet Lamps for Use in HVAC&R Units or Air Ducts to Inactivate Microorganisms on Irradiated Surfaces)*. IES and ASHRAE are also working on additional application guidance documents for upper room disinfection and other applications.

What types of products are on the market?

The COVID-19 pandemic has renewed interest in UV disinfection and many consumer grade and commercial grade products are being brought to market. Many of these products make claims with regards to specific pathogens and targeted disinfection levels based on rated product use. UL, NEMA and the American Lighting Association (ALA) recently released a position paper warning of improper use of consumer-oriented UVGI devices (Underwriters Laboratory (UL), American Lighting Association (ALA), National Electrical Manufacturers Association (NEMA), 2020). Manufacturers with verifiable performance claims should be willing to share supporting documentation with specifiers.

Some recognizable multinational lamp manufacturers have been producing linear and long twin tube UVGI lamps for many years and have made detailed technical specifications and guidance documents available. Similarly, some specialty manufacturers have been manufacturing UVGI products for upper room and HVAC applications for many years.[32]

Some LED luminaire manufacturers are incorporating UVGI, UVA, or short-wavelength disinfection sources into standalone products or combination products where disinfection sources are available alongside white-light channels. As previously noted, these devices should have a safety certification related to their spectrum, type of device, and installation environment.

[31] There are also development efforts to develop antimicrobial finishes that can inactivate bacteria on these surfaces when illuminated by UVA or visible light. See for example: https://www.nature.com/articles/s41598-018-38291-y
[32] IUVA has a Buyer's Guide available. The DLC has not conducted performance verifications for any ultraviolet disinfection product and cannot verify any of the performance data. https://uvsolutionsmag.com/buyersguide/

Conclusion

Though UV irradiation is a promising method for inactivating pathogens, specifically SARS-CoV-2, appropriate safety considerations are of utmost importance when installing, commissioning, maintaining, and using UV disinfection technology. This whitepaper should be used as a starting point to research appropriate, effective, and safe uses of UV irradiation for disinfection in commercial, industrial, and healthcare settings. The full list of recommended questions to ask all manufacturers before purchasing UV disinfection technology is provided below. A list of recommended further reading is also provided in the resources section.

What questions should be asked about UV disinfection before installation?

1. What are the wavelengths used in the product for disinfection? Specifiers should ask for a spectral power distribution (SPD).
2. What is the optical power (in W or mW) of the product? If the product being evaluated is a luminaire, the luminaire output should be given accounting for all optics (not just lamp output).
3. What is the input power and efficiency (optical power/input power) of the product?
4. How is the product used in application (continuous use, on until target dose is achieved, etc.)?
5. How many hours per use/day/year will be needed?
6. What pathogens are inactivated by the product and what is the target dose and disinfection rate for each? Is there peer-reviewed supporting documentation behind the claims?
7. What is the effective distance at which the target dose is given, and what is the irradiance at that distance?
8. What is the rated life of the product and how is it calculated (e.g. L_{70}, B_{50} (failure rate at which 50% of a large sample fail), etc.)?
9. What is the optical power depreciation of the product over the rated life?
10. What are the safety features and considerations of the product? Does it need to be installed with other sensors or controls to be used safely? What are the performance specifications on the controls and sensors?
11. Does the product produce ozone in the application? This may be a bigger issue for small spaces where products are operating continuously (like air-handlers or small rooms).
12. What safety certifications are provided for the products?
13. How is the system installed and commissioned to ensure the target dose is achieved?
14. How is the system maintained and what indications are provided when lamp or luminaire replacement is needed?

Resources

The following resources are recommended for a deeper understanding of the performance characteristics and photobiological considerations of UV disinfection, as well as for providing design guidelines.

ASHRAE

- ASHRAE Position Document on Infectious Aerosols
https://www.ashrae.org/file%20library/about/position%20documents/pd_infectiousaerosols_2020.pdf
- ASHRAE Position Document on Filtration and Air Cleaning
https://www.ashrae.org/file%20library/about/position%20documents/filtration-and-air-cleaning-pd.pdf
- 2020 ASHRAE Handbook—HVAC Systems and Equipment, Chapter 17, Ultraviolet Lamp Systems[33]
https://www.ashrae.org/file%20library/technical%20resources/covid-19/i-p_s20_ch17.pdf
- 2020 ASHRAE Handbook—HVAC Systems and Equipment, Chapter 62, Ultraviolet Air and Surface Treatment
https://www.ashrae.org/file%20library/technical%20resources/covid-19/i-p_a19_ch62_uvairandsurfacetreatment.pdf
- ASHRAE Standard 185.1-2020 - Method of Testing UV-C Lights for Use in Air-Handling Units or Air Ducts to Inactivate Airborne Microorganisms.
https://webstore.ansi.org/standards/ashrae/ansiashraestandard1852015
- ASHRAE Standard 185.2-2020 -- Method of Testing Ultraviolet Lamps for Use in HVAC&R Units or Air Ducts to Inactivate Microorganisms on Irradiated Surfaces
https://www.techstreet.com/ashrae/standards/ashrae-185-2-2020?product_id=2185696
- ASHRAE Technical Resources: Filtration/Disinfection
    - Ultraviolet Energy: https://www.ashrae.org/technical-resources/filtration-disinfection#uvc
    - UVC-LEDs: https://www.ashrae.org/technical-resources/filtration-disinfection#leds
    - UV-C In-Duct Air Disinfection: https://www.ashrae.org/technical-resources/filtration-disinfection#induct
    - UV-C Upper-Air Disinfection: https://www.ashrae.org/technical-resources/filtration-disinfection#upper
    - UV-C In-Duct Surface Disinfection: https://www.ashrae.org/technical-resources/filtration-disinfection#surface
    - UV-C Portable Room Decontamination: https://www.ashrae.org/technical-resources/filtration-disinfection#portable
    - Pulsed Xenon (Pulsed UV): https://www.ashrae.org/technical-resources/filtration-disinfection#pulsed
    - 405 nm Visible Light: https://www.ashrae.org/technical-resources/filtration-disinfection#405nm

[33] ASHRAE Handbook chapters with SI units available here: https://www.ashrae.org/technical-resources/ashrae-handbook-content

- Far Ultraviolet: https://www.ashrae.org/technical-resources/filtration-disinfection#far
  Special Precautions: https://www.ashrae.org/technical-resources/filtration-disinfection#special

GLOBAL LIGHTING ASSOCIATION (GLA)

- Position Statement on Germicidal UV-C Irradiation. May 2020. https://www.globallightingassociation.org/images/files/publications/GLA_UV-C_Safety_Position_Statement.pdf
- Germicidal UV-C Irradiation. Sources, Products and Applications. September 2020. https://www.globallightingassociation.org/images/files/GLA_-_Germicidal_UV-C_Irradiation_Sources_Products_Applications.pdf

IES

- IES-CR-20-V1 IES Committee Report: Germicidal Ultraviolet (GUV) –Frequently Asked Questions https://www.ies.org/standards/committee-reports/ies-committee-report-cr-2-20-faqs/
- Germicidal Ultraviolet Disinfection in the Days of COVID-19 (Webinar) https://www.ies.org/standards/committee-reports/
- Introduction to Ultraviolet and Visible Radiation Disinfection (Webinar) https://www.ies.org/standards/committee-reports/

CIE

- CIE position statement on the use of ultraviolet (UV) radiation to manage the risk of COVID-19 transmission http://cie.co.at/publications/cie-position-statement-use-ultraviolet-uv-radiation-manage-risk-covid-19-transmission
- CIE releases two UV publications available for free to support the global action to reduce transmission of COVID-19 (CIE 187:2020 Photocarcinogenesis Risks from Germicidal Lamps and CIE 155:2003 Ultraviolet Air Disinfection) http://cie.co.at/news/cie-releases-two-key-publications-uv-disinfection

INTERNATIONAL ULTRAVIOLET ASSOCIATION (IUVA)

- IUVA COVID-19 FAQ https://iuva.org/iuva-covid-19-faq
- IUVA Fact Sheet on UV Disinfection for COVID-19 https://iuva.org/IUVA-Fact-Sheet-on-UV-Disinfection-for-COVID-19/
- Advice for the selection and operation of equipment for the UV disinfection of air and surfaces https://iuva.org/Advice-selection/operation-of-equipment-for-the-UV-disinfection-of-air-and
- Expert Perspectives on UV as a Tool for N95 Decontamination Webinar https://iuva.org/Expert-Perspectives-on-UV-as-a-Tool-for-N95-Decontamination-Webinar
- Ultraviolet Solutions Magazine, the Official Publication of International Ultraviolet Association https://uvsolutionsmag.com/
- IUVA Draft Guideline IUVA-G01A-2005 General Guideline for UVGI Air and Surface Disinfection Systems https://www.researchgate.net/profile/Wladyslaw_Kowalski/publication/242516745_IUVA_Draf

t_Guideline_IUVA-G01A-2005/links/5653354208aefe619b1928cd/IUVA-Draft-Guideline-IUVA-G01A-2005.pdf

- Far UV-C in the 200 – 225 nm range, and its potential for disinfection applications https://iuva.org/resources/covid-19/Far%20UV-C%20in%20the%20200%20_%20225%20nm%20range,%20and%20its%20potential%20for%20disinfection%20applications.pdf

UNDERWRITERS LABORATORIES (UL)

- UL1598 Annex L, Standard for Safety, Luminaires, Additional Requirements for Germicidal Equipment https://standardscatalog.ul.com/ProductDetail.aspx?productId=UL1598
- UL1598 Annex M, Standard for Safety, Luminaires, Additional Requirements for UV Emitter Assemblies https://standardscatalog.ul.com/ProductDetail.aspx?productId=UL1598
- UL8802, Outline of Investigation for Germicidal Systems https://standardscatalog.ul.com/ProductDetail.aspx?UniqueKey=37651
- Ultraviolet-C (UVC) Germicidal Devices: What Consumers Need to Know. https://www.nema.org/docs/default-source/about-us-document-library/ultraviolet-c-germicidal-devices-what-consumers-need-to-know49f3889e-3ca2-4c2a-bc78-e74e78db76a7.pdf?sfvrsn=a50967d5_3

EPA

- Pesticide Devices: A Guide For Consumers https://www.epa.gov/safepestcontrol/pesticide-devices-guide-consumers
- EPA Compliance Advisory May 2020 - What You Need to Know Regarding Products Making Claims to Kill the Coronavirus Causing COVID-19 https://www.epa.gov/sites/production/files/2020-05/documents/cornavirus-compliance-advisory.pdf
- EPA Compliance Advisory October 2020 - EPA Regulations About UV Lights that Claim to Kill or Be Effective Against Viruses and Bacteria https://www.epa.gov/sites/production/files/2020-10/documents/uvlight-complianceadvisory.pdf

OTHER

- Kowalski, W. (2009). Ultraviolet Germicidal Irradiation Handbook. New York: Springer. https://link.springer.com/book/10.1007/978-3-642-01999-9
- National Institute for Occupational Safety and Health (NIOSH) Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings https://www.cdc.gov/niosh/docs/2009-105/pdfs/2009-105.pdf?id=10.26616/NIOSHPUB2009105

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