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Abstract

This publication includes information on products that produce optical radiation at specific ultraviolet (UV) or very short visible wavelengths, designed for use in disinfecting indoor building surfaces and/or air. Three key aspects of UV disinfection are considered throughout the document: product effectiveness, radiation safety, and energy use in buildings.

The publication is organized into a question-and-answer format. Questions were developed based on the results of a survey sent by the Lighting Research Center (LRC) to lighting stakeholders in June 2020. Important aspects of UV disinfection discussed in the publication include the wavelengths of optical radiation commonly used for disinfection, key characteristics of UV disinfection products currently on the market, field measurement and assessment of UV disinfection products, and currently available codes and regulations pertaining to these products.

The publication also provides a concise guide for professionals who are considering the specification of UV disinfection products in buildings, including a discussion on selecting the dose of UV radiation needed to inactivate various types of pathogens (viruses, bacteria, or fungi). Finally, the publication includes the results of LRC testing of twelve UV disinfection products, representing a variety of product types. This analysis includes a review of manufacturer claims of product performance and well as LRC evaluation of other key attributes of product performance.

Introduction

This publication examines products that produce optical radiation with the aim of disinfecting indoor building surfaces or air. These disinfection products may produce optical radiation at specific ultraviolet (UV) or very short visible wavelengths. All of the products examined, even those that produce very short visible wavelengths, will be referred to in this publication as UV disinfection products.

Three key aspects of UV disinfection products are considered in this *Lighting Answers*: product effectiveness, radiation safety, and energy use in buildings. This publication will help product specifiers and users determine whether a disinfection product will actually provide UV disinfection for different pathogens (viruses, bacteria and fungi) and where it might be used for greatest effect (surfaces or air). Of course, it is equally important for product specifiers and end users to understand how to use these UV disinfection products without injury or harm to themselves and others. *Lighting Answers* has not previously addressed issues of safety, but this is such a critical issue for the use of UV disinfection products that an exception was made for this publication. Finally, as the use of UV disinfection products powered by electricity proliferates, it was important for this publication to consider the energy implications of product use.

This publication is organized into a question-and-answer format. Questions were selected based on the results of a survey sent by the LRC to lighting stakeholders on UV disinfection products in June 2020. Additional resources are included at the end of this document for those interested in learning more about UV disinfection products and systems.

Prior to the question-and-answer section, a topic overview provides a helpful orientation to this publication. It is important to, first, understand the significance of dose when assessing the effectiveness, safety, and energy use of UV disinfection products and, second, to have a guide to specifying the most effective, safest, and most energy-efficient approach for UV disinfection.

Overview

Dose

When considering UV disinfection technologies, it is important to define the *dose* needed to achieve disinfection. Dose is the density of optical radiation energy; it is the product of irradiance and the duration of exposure at the wavelength effective for inactivation of the pathogen. Dose is measured in units of joules per square meter ($J\ m^{-2}$). Figure 1 shows that the required dose depends on the susceptibility of the microorganism (virus, bacterium, or fungus) to 254 nm. Figure 1 was developed for 254 nm because this is the primary wavelength generated by low-pressure discharge mercury (Hg) lamps, currently the most widely used source of UV disinfection radiation. Use of other wavelengths or multiple/broadband wavelengths would have different results.

Figure 1 shows that airborne viruses such as SARS-CoV-2 are particularly susceptible to optical radiation at 254 nm. However, there is a wide range of doses needed to inactivate different viruses, bacteria, and fungi.

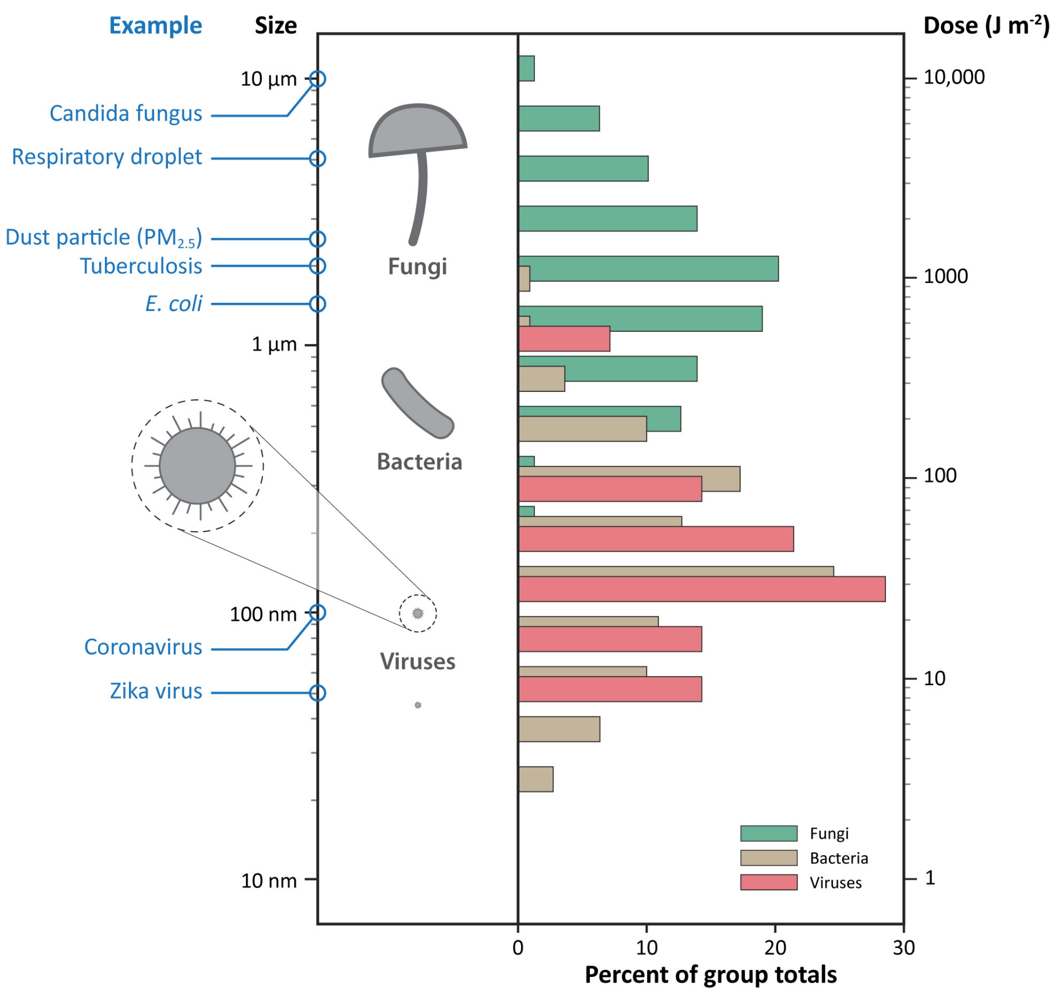


Figure 1. Dose of ultraviolet germicidal irradiation (at 254 nm) for various microorganisms

In general, UV radiation has two modes of action for disinfection: direct and indirect.

Direct damage to the pathogen is mostly due to absorption of UV radiation by the pathogen's DNA or RNA. The peak spectral absorption for direct damage to DNA and RNA is between 260 nm and 270 nm. To produce the same direct damage to a pathogen, a low-pressure mercury discharge lamp that emits radiation at 254 nm would need a 25% greater dose than an LED with a peak emission at 265 nm. For direct disinfection, the following equation models the degree of disinfection accurately up to about a 99.9% disinfection level for a particular pathogen and UV source. Higher disinfection levels require models with more terms to account for genetic diversity of UV resistance within a pathogen species.

$$\text{Survival fraction} = (1 - \text{Disinfection level}) = \frac{N_R}{N_O} = \exp(-kD)$$

Where N_R/N_O is the ratio of the number of infectious pathogens remaining after treatment (N_R) over the number of infectious units without treatment (N_O), D is the UV dose (J m^{-2}), and k is a rate constant (m^2 J^{-1}) that models the sensitivity of the pathogen to a specific UV wavelength band. Values of k for different pathogens vary with the mode of disinfection (air, surface, or water) and the environmental conditions, mainly temperature and humidity.

Indirect damage to a pathogen is caused by UV absorption by photopigments, either within the pathogen or in the pathogen's immediate environment. Chemical reactions to the UV radiation can generate reactive oxygen species, like hydrogen peroxide (H_2O_2), that break down proteins within the cell or at cell walls. A wide range of UV wavelengths (including very short visible light) can support indirect disinfection because different photopigments have many different spectral absorption bands. Indirect disinfection can also occur if the UV source produces ozone, which also breaks down cell walls. Less is known about disinfection rate constants for indirect UV disinfection, especially when the process depends on an exogenous photopigment of unknown availability. In general, the doses required for UV-A and very short visible light are much greater, typically several hours of exposure at similar irradiance levels, than for higher energy UV-C sources, which typically require only a few minutes.

Dosing for surfaces and air are different. For surface disinfection, irradiance is a measure of UV radiant power incident on a planar surface. Pathogens suspended in air receive UV radiant power from all directions. The term *fluence rate* is used to quantify the UV dose for airborne pathogens. Fluence rate is defined as the flux incident on an imaginary sphere divided by the cross-sectional area of that sphere (πr^2) in the limit as the radius (r) of the sphere approaches zero. Fluence and planar irradiance have the same units, W m^{-2}, so fluence and planar dose have the same units, J m^{-2}.

When disinfecting air, the fluence rate can be significantly increased by adding UV reflective materials, such as aluminum, to the surrounding surfaces, thereby increasing the dose. It should be remembered, however, that these reflecting surfaces may also increase the likelihood of exposing human skin and eyes to UV radiation.

Specification Guide

The first two steps in the disinfection system specification process are to determine, first, whether the pathogen of concern is primarily on surfaces or in the air and, second, whether disinfection can be achieved when the space is occupied. Table 1 summarizes the choices and effects.

Table 1. UV disinfection specification guide

Pathogen location	**Occupied spaces**	**Unoccupied spaces**
Air	**Viruses, Bacteria** Direct inactivation • UV-C (shielded or low irradiance) or far UV-C (unshielded) Electrical energy use • Low	**Viruses, Bacteria** Direct inactivation • UV-C or far UV-C Electrical energy use • Low
Surfaces	**Bacteria, Fungi** Indirect inactivation • UV-A or short-wavelength visible Electrical energy use • High	**Bacteria, Fungi** Direct inactivation • UV-C Indirect inactivation • Ozone (0_3) Electrical energy use • Medium

In medical facilities such as hospitals and clinics, healthcare associated infections (HAIs) are caused primarily by bacteria and fungi that persist on surfaces; viruses are of less concern on surfaces. HAIs are transmitted to people primarily by touching the surface and then touching an open wound or the face. Manual cleaning with chemicals is effective but is not always consistently administered. Similarly, optical radiation is not always effective because pathogens may lie in the shadow of a surface and even in the shadow of microscopic surface irregularities. Therefore, to kill bacteria and fungi on surfaces, routine manual cleaning should be supplemented with UV or short-wavelength visible radiation. Within limits, disinfection can be achieved without exceeding published limits on UV exposure in occupied spaces if UV-A or 405 nm energy bands are employed.

Infection by viruses, like the coronavirus responsible for COVID-19, or bacteria, like tubercle bacillus (TB), occurs primarily by inhalation of airborne virus particles shed by another person in close proximity. High ventilation rates will minimize exposure to airborne pathogens. If high ventilation is impractical and deactivating the pathogen in an occupied space is important, a UV-C system that deactivates pathogens while airborne in the space should be used. To accomplish this goal without exceeding published limits on UV exposure, a UV-C system with maximum emission between 254 nm and 275 nm that irradiates room air while strenuously minimizing potential direct exposure of skin or eyes from the source should be selected. Such systems have been used successfully in buildings for many years using one of two possible strategies. The first is to treat the air with UV-C sources in the duct work; these are known as in-duct systems. The second is to treat the air from baffled

UV-C sources mounted on the wall; these are known as upper-room systems. Both of these systems will be most effective when they augment frequent replacement of room air that has been contaminated by occupant exhalation with fresh air. Two recent UV-C innovation air disinfection technologies have been developed and are being tested. One provides low 265 nm irradiance levels in occupied spaces, thus requiring long exposure times to meet the prescribed dose. The other provides far UV at approximately 222 nm that is presumably safe for human skin and eyes.

The next step in the specification process is to define the required dose. Dosing is difficult to define in practice because: 1) pathogens vary considerably in their sensitivity to optical radiation; 2) different mechanisms of disinfection occur at different regions of the energy spectrum and, thus, require different amounts of optical radiation; and 3) the material immediately surrounding the pathogen and the environment (temperature and humidity) affect the pathogen's susceptibility to optical radiation. Furthermore, a prescribed inactivation dose will vary considerably depending upon the desired pathogen disinfection level [e.g., 90% ("1 log kill") or 99% ("2 log kill")]. Complicating the specification, published inactivation doses for specific viruses, bacteria, and fungi vary considerably because of the methods used to obtain those estimates. Since there are no "closed loop" systems that adjust dose based upon measured inactivation of the pathogen, it is important to perform periodic measurements of pathogen presence to determine if the prescribed dose is achieving expected results. This can be a relatively slow process, but it is the most important way to determine if the dosing is effective. Then, based upon the prevalence of the target pathogen, each of the variables identified above can be adjusted to obtain the desired results.

Specifier Survey

To inform the development of this publication, the LRC administered an online survey. The survey was sent out electronically to a diverse set of lighting decision makers using an existing LRC-maintained email list. Responses to the survey were received from 208 people in June and July 2020.

The largest percentage of respondents was lighting specifiers (38%), followed by lighting manufacturers (28%). Also responding were energy service personnel (11%) and lighting manufacturers' representatives and distributors (9%). A few responses came from educators (8%), architects (3%), HVAC professionals (2%), and architectural engineers (1%).

Respondents were asked to select what they believed to be the three most promising types of UV disinfection products (Figure 2). The most popular choices were: upper-room air purification (58%), in-duct air purification (55%), surface disinfection integrated with light fixtures (45%), and surface disinfection from (dedicated) wall- or ceiling-mounted products (40%).

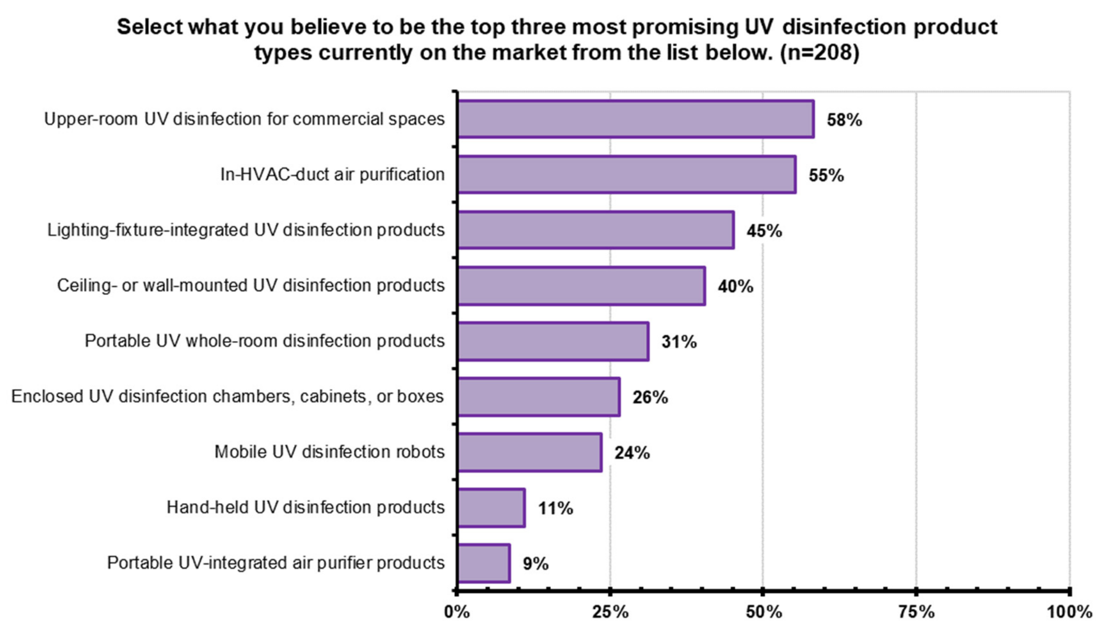


Figure 2. Survey respondents' opinions about most promising UV disinfection products

Survey respondents were also asked to select what they viewed as the three most promising application types for UV disinfection (Figure 3). Most respondents (83%) selected healthcare applications. Half (50%) thought that transportation and long-term care (i.e., nursing home) facilities were a promising application for UV disinfection systems. Less than a third of respondents selected schools and colleges (33%), restaurant food service (31%), and office buildings (26%) among their top three rated application types.

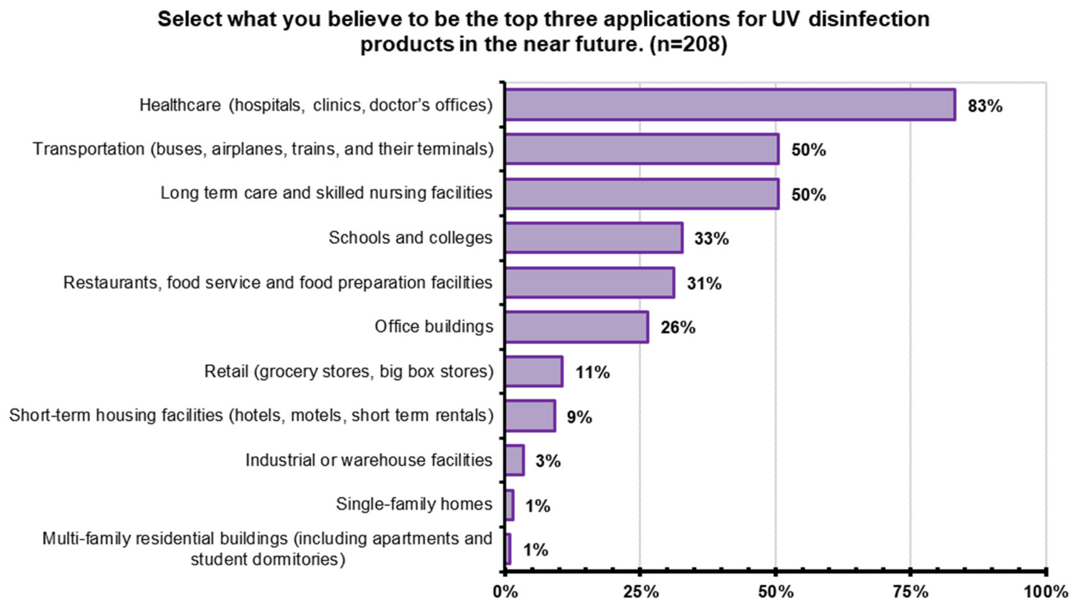


Figure 3. Survey respondents' opinions about most promising application types for UV disinfection

Finally, respondents were asked to select the three greatest concerns they had with UV disinfection technologies (Figure 4). Most respondents (81%) were concerned about product safety. Also of concern were field verification of effectiveness (62%) and overall effectiveness of UV products (53%). A third of respondents were concerned about damage to materials (33%) and the lack of clear building safety codes for use of UV disinfection in buildings (31%). Of lesser concern were ongoing maintenance (17%), high product cost (14%), and energy use (9%).

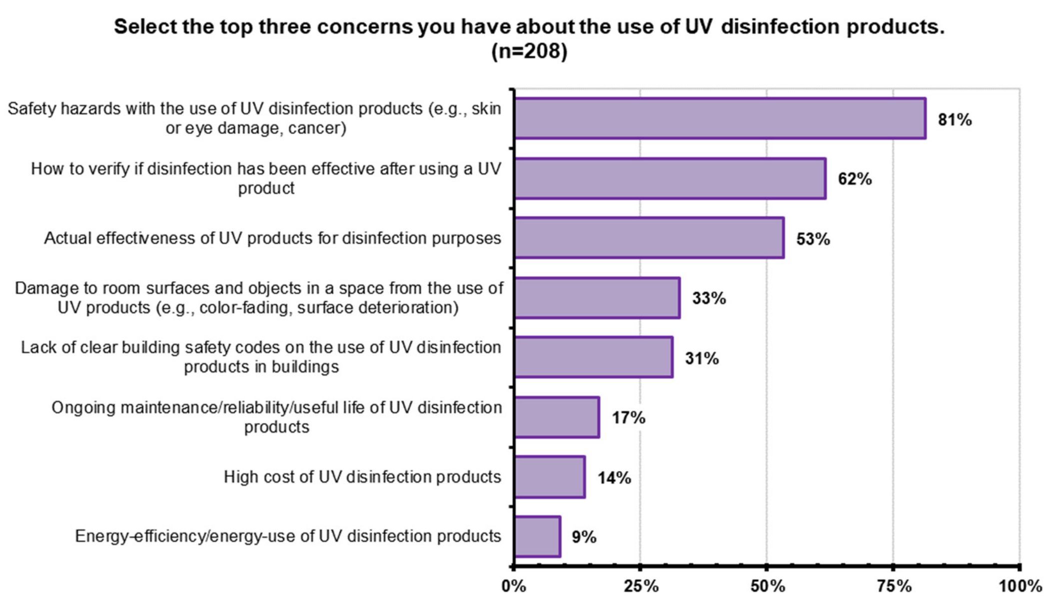


Figure 4. Survey respondents' most prevalent concerns

What is the full range of wavelengths used for disinfection, and what is the effectiveness of each?

Because spectral emission of UV sources is a major component of UV dose calculations, this publication begins with spectral considerations. The Illuminating Engineering Society (IES) defines UV radiation as radiant energy within the wavelength range of 10 nm to 400 nm. UV energy is generally considered electromagnetic radiation shorter than that of visible light but longer than X-rays. Within this range, wavelengths that have been used for disinfection purposes extend from about 185 nm up to about 405 nm. Table 2 below divides this range of UV energy into smaller increments and includes information about the light sources that produce energy within each range and the typical uses, benefits, and drawbacks of each.

Table 2. Wavelengths used for disinfection and characteristics of each

	UV-C (100 – 280 nm)		UV-B (280 – 315 nm)	UV-A (315 – 400 nm)	Visible Light (>380 nm)
	Far UV-C (200 – 230 nm)	*Traditional germicidal (254 nm)*		*Antibacterial products (350 – 405 nm)*	
Sources	Krypton chlorine excimer, Xenon	Medium- and low-pressure discharge Hg, LED, Xenon	Sunlight, Hg, LED, Xenon	Sunlight, LED, Xenon	Sunlight, LED, Xenon
Typical uses	Germicidal (viruses, bacteria, and fungi)	Germicidal (viruses, bacteria, and fungi)	Tanning booth, Vitamin D production, material curing, psoriasis treatment	Bactericidal, blacklight theatrical effects, material curing	Bactericidal, material curing
Benefits	Preliminary results indicate safe for human skin and eyes	Many decades of successful use (LPD Hg) disinfecting. Some also produce disinfecting ozone	Most medically active spectral region	Space can be occupied during operation at prescribed doses	Benign for skin; space can be occupied during application
Drawbacks	Long-term impact on eyes/cornea unknown; International UV Assoc. recommends more research before deployment in occupied spaces	Must be used as an indirect or enclosed source or space must be unoccupied; no humans, pets, or houseplants should be present when used directly in a space	Greatest risk for skin and eye damage	Requires long exposure times or high irradiances to be effective	Requires long exposure times or high irradiances to be effective
	Low energy efficiency	Material degradation	Material degradation	Material degradation	Damage to light-sensitive materials
		If produces ozone, additional safety precautions needed		May contribute to skin aging	

Table 2. Wavelengths used for disinfection and characteristics of each (cont.)

	UV-C (100 – 280 nm)		UV-B (280 – 315 nm)	UV-A (315 – 400 nm)	Visible Light (>380 nm)
	Far UV-C (200 – 230 nm)	*Traditional germicidal (254 nm)*		*Antibacterial products (350 – 405 nm)*	
Drawbacks (cont.)	User concerns about UV technologies	User concerns about UV technologies		User concerns about UV technologies	User concerns about UV technologies
				Requires an adjunct (e.g., TiO_2) to be effective.	May depend on an adjunct (e.g., TiO_2) to be effective
	Line of sight technology	Line of sight technology; few materials reflect UV-C Deep crevices in textured surfaces not likely to receive disinfection		Line of sight technology; limited materials reflect UV-A	Inter-reflections possible
Disinfection of surfaces	Yes	Yes		Primarily, and if other adjuncts present	Primarily, and if other adjuncts present
Disinfection of air	Yes	Yes		May depend on an adjunct (e.g., TiO_2) to be effective	Possibly, if adjunct present
Effective against viruses	Yes	Yes		Not primarily*	Not primarily*
Effective against bacteria/fungi	Yes	Yes		Yes	Yes

*Some evidence of effectiveness against non-enveloped viruses (e.g. norovirus), by means of secondary reactive oxygen species.

What electric light source technologies are currently on the market that produce energy in the UV region of the spectrum?

Table 3 below provides information on each of the most common electric light sources that produce UV radiation.

Table 3. UV disinfection source types

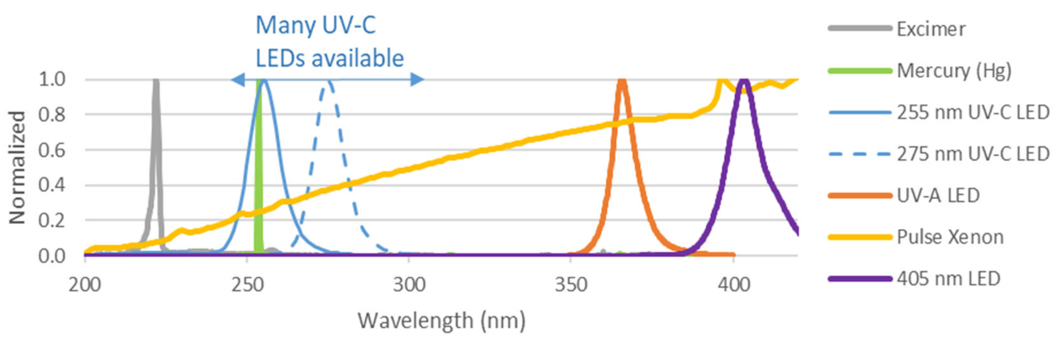
	Excimer	Mercury (Hg)	LED	Pulse Xenon
Produces UV by…	Spontaneous emission from pairs of molecules that only combine in the excited state and release quasi-monochromatic UV photons when transition to the ground state	Spontaneous emission from excited Hg atoms within a transparent specialized glass, no phosphor	Spontaneous emission from a wide bandgap semiconductor P-N junction (GaN or AlGaN material)	Spontaneous emission from excited xenon gas at high pressure that is rapidly ionized by a high voltage and current pulse
Spectral power distribution				
Lamp types, shapes	Discharge source; Cylinder 3-in to 18-in length; most common type is krypton-chlorine with a peak emission at 222 nm. Some products use narrow band filters to further limit the emission of radiation beyond 230 nm	Discharge source; linear, biaxial, or electrodeless (similar to conventional fluorescent)	Solid-state electronic devices (chips); small point source often with integrated optics and output in a particular direction	Discharge source; linear and circularly bent tubing of various sizes, typically from a few to tens of cm in length; some products flash 10 times per minute

Table 3. UV disinfection source types (cont.)

	Excimer	Mercury (Hg)	LED	Pulse Xenon
Thermal characteristics	Output is somewhat sensitive to temperature. Some high-power commercial products are air cooled	Optimal temperature operating range. Increases output as it warms up and stabilizes; high output (electrodeless induction) may stabilize at higher temp, reducing output	Short- and long-term performance depends on junction temperature. Output *reduces* as junction temperature increases	Not used continuously, but rather, flashing
Electrical operation issues	Operates at high voltage and often at high frequency	Potential for EMI, RFI	Low voltage, dc sources. Operates best under constant current conditions. Sensitive to reverse voltage bias and electrostatic discharges	Power demand can vary significantly with time depending on flash rate and duty cycle. Potential for EMI, RFI
Safety, other than UV exposure	High voltage, potential for ozone	If lamp breaks, mercury cleanup per EPA guidelines; Potential for ozone	N/A	Flashing can be startling and disorienting. High voltage. Potential for ozone

What are the most common types of UV products on the market?

Table 4 below provides information on several common types of UV-emitting products.

Table 4. Common types of UV-emitting products

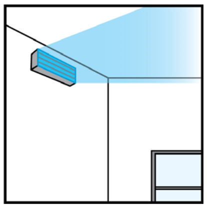
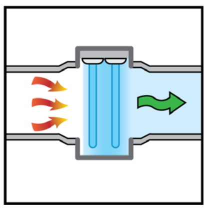
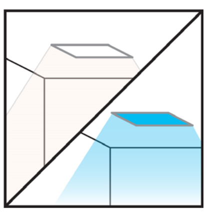
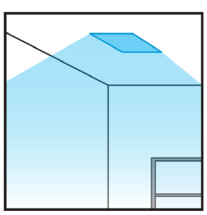
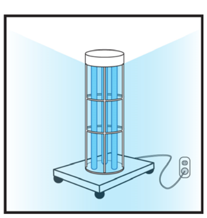
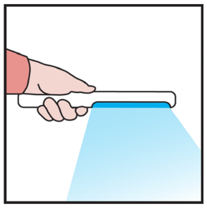
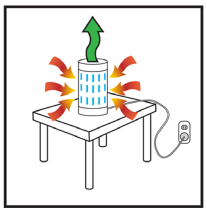
	Technologies available	**Operation**	**Common uses**	**Effective for**	**Potential safety concerns**	**Keep in mind**
Upper room 	LPD Hg, some LED	Disinfects a zone above typical head height. Relies on building airflow for effectiveness	Air disinfection in public congregation spaces	Airborne bacteria, viruses	Accidental exposure (people on ladders, bunk beds)	Air speed, volume, and direction impact exposure duration. Low optical efficiency; works best in high-ceiling spaces
In-HVAC-duct 	LPD Hg	Located in HVAC duct	Commercial spaces	Airborne fungi, bacteria, viruses	UV damages HEPA filters	Maintenance: Out of sight, out of mind
Hybrid with lighting fixture 	LPD Hg, LED, krypton-chlorine excimer	Turn on UV channel when unoccupied (UV-C) or occupied (UV-A, indigo, excimer)	Healthcare; could also be used in schools, offices, or other spaces with strictly scheduled use if using UV-C	Surfaces: bacteria, viruses, fungi: localized air disinfection devices	UV-C: Protect desired living organisms (night staff, pets, office plants) from exposure	Due to dosage limits, most require controls which are not always reliable; photodegradation of materials, possible elevated ozone
Ceiling- or wall-mounted (dedicated) disinfection 	LPD Hg, electrode-less induction Hg, LED, excimer, pulse xenon	When unoccupied (UV-C) or occupied (UV-A, visible 405 nm or excimer 222 nm)	Healthcare; could also be used in schools, offices, or other spaces. If UV-C, space must have strictly scheduled use	Surfaces: bacteria, viruses, fungi: localized air disinfection devices	UV-C: Protect desired living organisms (night staff, pets, office plants) from exposure; residual ozone effects	Due to dosage limits, most require controls which are not always reliable; photodegradation of materials, possible elevated ozone
Portable whole-room sanitizer 	LPD Hg, pulse xenon	Position in room, set controls, depart and lockout/tagout room; return later to setup in next space	Healthcare, transportation; could also be used in schools, offices, other night cleaning; hotels require faster turnaround by unskilled labor	Surfaces: bacteria, viruses, fungi	UV-C: Do not expose any living tissue (pets, children, night staff); possible residual ozone effects	Shadowing; photodegradation of materials so not suitable for retail; labor-intensive to move to multiple spaces

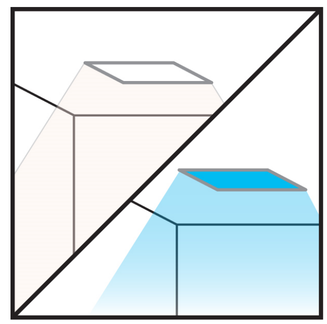
Table 4. Common types of UV-emitting products (cont.)

	Technologies available	Operation	Common uses	Effective for	Potential safety concerns	Keep in mind
UV wand 	LPD Hg, LED	Hold over surfaces or objects (desk, bed, etc.)	Desk, hotel surfaces, personal electronics	Small surfaces at close range	UV-C: Do not expose any living tissue (children, cleaning staff, pets)	Small areas; ineffective for short durations
Portable air purifier 	LPD Hg, LED	Small-medium room	Healthcare/ dental exam room, private office, indoor reception/event spaces	Air disinfection	Some products poorly constructed, with "light leak"; possible ozone effects over time if left running for long periods	Less effective than upper room disinfection for large volumes of air. Choose model with 0.25-2.5 air changes per hour for room volume

How effective are various types of products at providing disinfection?

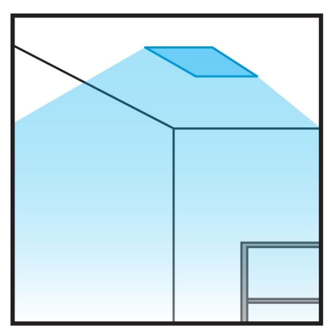
The survey results rank-ordered priorities for disinfecting products. Upper room and in-duct UV systems are a mature technology with decades of field data available (Kowalski 2009); the LRC did not perform additional testing of these product types.

The LRC tested three hybrid products (UV + visible light), four dedicated ceiling- and wall-mounted UV products, two portable whole-room sanitizers, a portable air purifier, and two UV wand products. The LRC also tested a UV measurement card product. Summaries of these results are shown below, and details of testing procedures are shown in Appendix A. Test results are shown in Appendix B. For a given required dose, the UV-C products are expected to be considerably more effective at bacterial disinfection (roughly a thousand times the efficacy) relative to power demand of UV-A and visible disinfection products; however, occupants cannot be exposed to most UV-C products without exceeding published limits for exposure.



Hybrid UV fixtures: The hybrid products that the LRC tested were each designed to emit different wavelengths to achieve disinfection.

- Hybrid product A emitted UV-A (365 nm) from a lensed 2x2 recessed troffer. This engineering sample was a product intended to address surface bacteria, not airborne viruses. This product emits UV-A downward at a high intensity and is designed to operate for extended durations within specified safety limits (e.g., ACGIH and others).
- Hybrid product B emitted UV-C (254 nm) from a central segment of a 2x2 basket-type troffer. Due to a polished aluminum reflector, its distribution is downward and oblong. This product is expected to disinfect surfaces more quickly than the UV-A and visible products, but it cannot be used while the space is occupied. This was the only product of the three hybrid products that was practically capable of addressing virus disinfection.
- Hybrid product C emitted visible violet light (405 nm) from a 7-inch diameter recessed downlight. This product is intended to address surface bacteria, not airborne viruses. It diffusely emits 405 nm light in a Lambertian distribution. It is intended to operate continuously, whether or not a small space (e.g., shower stall) is occupied.

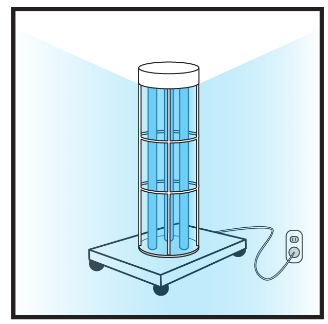


Ceiling or wall-mounted UV fixtures: The LRC tested four products in this category, all of which emit UV-C. (The LRC also tested a broadband, pulse xenon product that can be used with permanent mounting; see “portable” section below.)

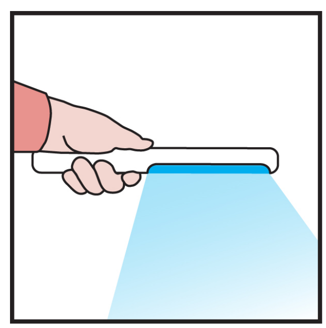
- Ceiling product A was a 4-inch recessed downlight that emitted far UV-C (222 nm). The engineering sample that LRC tested emits a low intensity of 222 nm far UV, does not include additional optical filters, and is intended for use on surfaces and air while occupied.

- Ceiling product B was an excimer lamp not integrated into a commercially available product and does not include additional optical filters. It emits 222 nm far UV-C with an intense, toroidal distribution.
- Ceiling product C was a large electrodeless lamp not integrated into a commercially available product. It emits 254 nm UV-C in a bi-lobed distribution. This lamp is expected to disinfect surfaces more quickly than the others in this category due to higher radiant output. This lamp would be suitable for mounting in commercial spaces or in its portable configuration, if controls (e.g., sensors) are not obstructed from view of approaching traffic. The LRC also measured considerable ozone production from this source, which would provide additional disinfection; however, post-treatment ventilation would be needed before a space could be occupied.
- Ceiling product D was a compact, surface-mounted UV-C LED device, similar in size to a smoke detector. The engineering sample that the LRC tested emitted UV-C at a very low output. This product is considered exempt from photobiological safety recommendations (ANSI/IES 2015) due to its low UV-C output, so it can be operated while occupied.

Portable whole-room sanitizers: The LRC tested two products in this category.

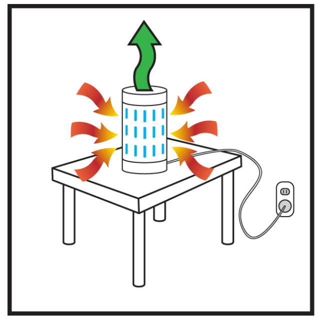


- Portable product A contained a biaxial LPD Hg lamp in a tower configuration. The enclosure cage and vertical lamp orientation caused the UV-C distribution to radiate mostly in a lateral direction. This product would be effective at disinfecting vertical surfaces surrounding the tower. This product produced ozone, which would provide additional disinfection; however, ventilation would be needed post-treatment before a space should be occupied.
- Portable product B used an intensely flashing pulse xenon source and is intended to be mounted on a tripod (or could be permanently mounted to a surface). It emits broadband output (including UV-C, UV-B, UV-A, and visible wavelengths), and thus much of its radiant power is emitted at wavelengths not especially effective for disinfection.



UV wands: The LRC tested two handheld UV wands advertised for use in commercial environments. LRC measurements were used to calculate how much time would be required to disinfect a full-sized hotel bed, a desk, or a laptop. Although one wand product emitted more UV-C than the other, both require impracticably long durations to be effective for disinfection in commercial settings. Even with wand movement, it should also be noted that deep crevices in textured surfaces (e.g., bedlinens, keyboards) would not likely receive considerable disinfection. On another important note, handheld wands were powered by battery, which may not have sufficient charge to be used for required durations. In order to perform testing, the LRC had to disable the batteries and power these wands externally.

- Wand A used a conventional LPD Hg source to create UV-C. This product lacked a reflector, instead providing a non-metallic plastic housing. This product was calculated to require 1.2 minutes to disinfect a laptop, 10 minutes to disinfect a desk, 22 minutes to disinfect a bed.
- Wand B used UV LEDs that generated both UV-C and UV-A. For this product, the LRC calculated particularly long durations required for disinfection. This product was calculated to require 12 minutes to disinfect a laptop, 1 hour 15 minutes to disinfect a desk, 2 hours 39 minutes to disinfect a bed.



Portable air purifiers: The LRC purchased two portable air purifiers; however, one actually emitted UV-A rather than UV-C as claimed, and thus was eliminated from further testing. As shown in Appendix B, the remaining air purifier uses two separately switched strategies to provide disinfection: UV-C and ozone. LPD Hg lamps provide UV-C that is contained within the device. The device has a fan that draws air through the housing. The UV-C feature can be used while the space is occupied because the lamps are shielded from view in an inner compartment. The UV-C disinfection level for a very small room (10 m^2, ~100 ft^2) with one air exchange per hour is only 0.9[1], barely achieving the lowest of typically expected levels of 0.9 or 0.99. Considering that this is a very small space and that suggested ventilation guidelines are on the order of five air exchanges per hour, the UV-only option is ineffective for disinfection. LRC test results indicate that the ozone feature of this product may provide greater air disinfection than the UV-C feature, but it should not be used while the space is occupied. This product also did not include reflectors to increase irradiation of air and did not shield internal wiring components from UV-C exposure.

Ozone (O_3)

Sources that emit wavelengths 175-240 nm may also generate ozone (O_3) (Alexander et al. 2003). While some "ozone-free" LPD Hg UV lamps block or reduce output from the 185 nm mercury emission line to prevent ozone production, other UV lamps are specifically designed to emit this ozone-producing wavelength. While also useful for disinfection, ozone is a health hazard to human occupants in enclosed spaces; occupants should not be present at levels above 0.1 ppm for 8 hours of light work, or 0.05 ppm for heavy work (ACGIH). Ozone can also affect materials. The LRC placed stretched rubber bands in a chamber generating ozone; the rubber bands broke in less than one hour. UV-C and UV-B sources will dissociate (split) the O_3 molecule, converting it back to breathable diatomic oxygen (O_2). The performance of a disinfection product that intentionally generates ozone may be compromised if UV-C lamps are also used in proximity. To promote effectiveness of both disinfection strategies, separate UV sources from ozone generation.

[1] For a k value of 0.118 (median value for airborne viruses from table published by the International UV Association). For airborne bacteria, the median k value is 0.217 leading to a disinfection rate of 0.98.

What performance standards are currently available for UV products?

As of 2020, performance standards have not been developed for UV products; specifiers are reliant on case studies and manufacturer claims to judge the effectiveness of specific UV products.

In the U.S., the Code of Federal Regulations Title 21 has a section addressing performance standards for light-emitting products. Section 1040.20 includes sunlamp products (i.e., sources ranging from 200 nm to 400 nm), but it is aimed at products intended to induce tanning, not disinfection. Title 21 limits output in the range of 260-320 nm.[2]

Underwriters Laboratories (UL) will certify some UV-C products for safety but not disinfection capability.[3] Eligible product types include those with contained UV-C sources, commercial/healthcare products, upper room UVGI, hybrid systems, UV-A, and visible disinfection technologies. UL does not certify the safety of portable sterilizers and wands in consumer/residential use.

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[2] https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?fr=1040.20

[3] https://www.ul.com/services/ultraviolet-uvc-light-testing-and-certification

How do I properly/safely measure UV and verify its effectiveness?

One method to determine if a UV system is providing effective disinfection is to measure and verify if the system is delivering the specified dose for the application. There are various means of verifying UV dose in the field.

Spectral output for these systems is measured with a spectroradiometer with optics and a sensor tuned to wavelengths ranging from 200 nm to 400 nm (Figure 5). UV radiant intensity can be estimated when spectral irradiance is measured with a calibrated instrument located at a known distance from a source, as per industry standards-setting organizations (ANSI/IES 2015, IEC 2006). The IES and the International Ultraviolet Association (IUVA) are jointly developing new measurement procedures to accurately measure new UV source types, UV products, and UV meters without exceeding exposure limits by personnel performing the measurements. Personal protective equipment is required when measuring UV-C (Figure 6). UV meters should have calibrations traceable to a national laboratory (e.g., NIST in the U.S.).

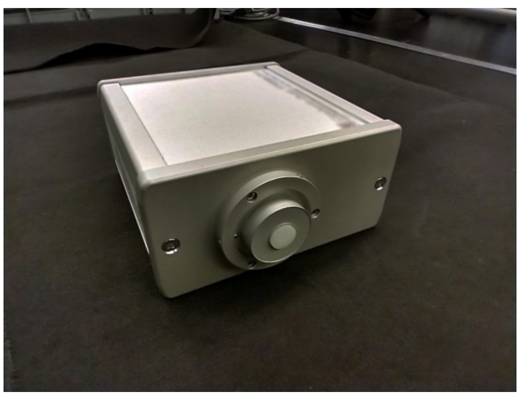


Figure 5. Commercial spectroradiometer capable of measuring irradiance in the 200 nm to 430 nm range

Figure 6. Personal protective equipment shields the skin and eyes from UV-C exposure

As with any light source, the output of UV sources will degrade over time. Manufacturer ratings for source life are significantly shorter for many low-pressure discharge (LPD) UV products (<10,000 h) than for conventional LPD fluorescent technology (>30,000 h). Although it is always important to check the product specifications to ensure meeting the intended UV output over time, it should be noted that independent testing by the LRC showed that the life of LPD UV lamps is comparable to LPD fluorescent lamps up to 10,000 hours.

Calibrated UV meters cost several hundred to many thousands of dollars depending on their capabilities and accuracy. As a proxy for a calibrated UV meter, measurement cards are available for one-time use (Figure 7). As shown in Appendix A, measurement cards can confirm that UV is present at a site at an intensity capable of disabling bacterial pathogens of concern in hospitals.

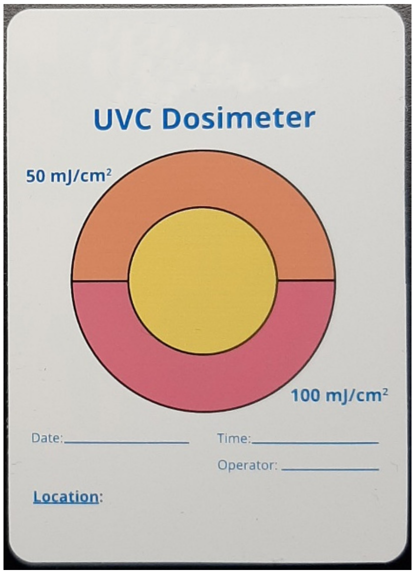


Figure 7. UV measurement card

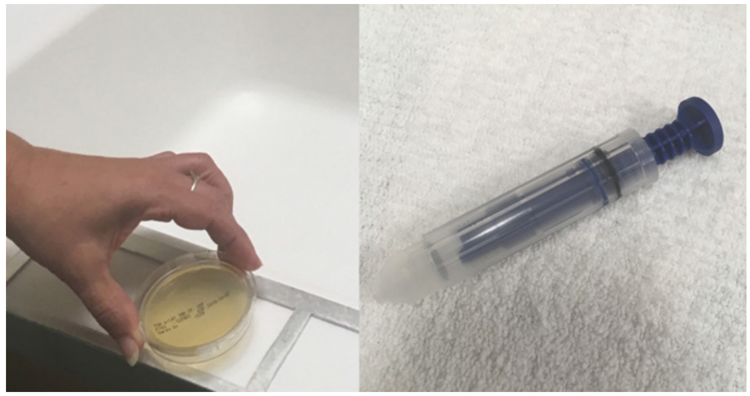


Figure 8. RODAC plate (left) and ATP swab (right)

Some UV sources emit ozone (those emitting power at wavelengths less than 240 nm). Ozone is measured with specialized chemical sensors. Exposure limits for ozone are established by the American Conference of Governmental Industrial Hygienists (ACGIH 2017).

A second method of verifying UV system effectiveness for surface disinfection is by sampling various pathogens present on the surfaces in the space.

There are three primary options for assessing the sanitary status of a given surface: swabbing and culturing, replicate organism detection and sampling (RODAC) plate testing, and adenosine triphosphate (ATP) measurement (Figure 8).

ATP is the molecular "fuel" that all living organisms use to carry out life processes. As such, the amount of ATP on a surface is an indication of the presence or absence of microbes on a surface. ATP measurement is the simplest, cheapest, and fastest method of the three, which uses a swab and handheld measurement device to quantify the amount of ATP present on a surface. The surface is swabbed and the sample is then inserted into the measurement device. An integrated fluorescent assay then measures how much ATP was collected. While useful for its incredible convenience, ATP measurement is by far the least robust of the three measurement options for a few reasons. First, ATP is found in all microorganisms, including completely benign examples such as common fungi and human skin cells. Thus, the ATP reading is not an indication of how many actual pathogens are on the surface, as the quantity displayed may be entirely composed of harmless organisms. Second, ATP measurement is poor at detecting viruses because viruses are not "alive" in the traditional sense, and thus do not carry out metabolic processes that require ATP. Third, ATP measurement does not differentiate between living or dead organisms; it simply detects organic matter, and thus does not reflect the density of microbes that are actually capable of being infectious.

Both swabbing and RODAC testing use agar plates to culture sampled microbes up to a workable population size. Because of this, these testing methods require 3 to 5 days of gestation time in a biological incubator before results will be available. The primary difference between the two methods lies in how samples are actually collected. Swabbing, as the name implies, uses a fiber swab that is dabbed or wiped on a plate to start the culture. In contrast, RODAC testing uses a convex-shaped agar plate in which the agar itself is placed onto the sampling surface to pick up any microbes present. Of the two, RODAC testing is more reliable and quantifiable, as the user cannot assess how much material has been transferred from the surface to a swab and from the swab to the plate. Furthermore, the density of microbes on the surface cannot be reliably quantified with swabbing because the area sampled will be non-standard. Despite the time investment required, swabbing and RODAC testing offer much more reliable and granular results, as the resultant culture can be further analyzed to determine precisely which organisms have formed the colonies present. In addition, dead organisms will not form colonies and will thus not contribute to the results obtained. These methods also face difficulties characterizing viruses because viruses do not form colonies.

It should be noted that differentiating between dead and living organisms may be a bigger concern in assessing UV sanitation than it would be in assessing traditional sanitation methods. In traditional chemical sanitation, the combination of chemically mediated cell lysis and actual physical wiping mean that inert cell bodies are generally destroyed or altogether removed from the surface being cleaned and are thus no longer present to be counted by a method like ATP measurement. In UV sanitation, microbes are typically inactivated or killed, rather than actually being destroyed, so the cell bodies of inactivated microbes may still be fully intact and present. They may thus still be detected by ATP measurement despite being properly sanitized by the UV treatment.

What codes and regulations exist governing the use of UV systems in buildings?

Several publications have been developed that address the safe use of UV systems in buildings (Figure 9). While no regulatory UV radiation exposure limits have been developed in North America, voluntary threshold limit values (TLVs) are published by the American Conference of Governmental Industrial Hygienists (ACGIH). These are designed to minimize workers' erythema (reddening) of the skin and photokeratitis ("snowblindness") of the eyes. This publication addresses both chronic (daily) occupational exposure at low levels, as well as acute (temporary) exposure. For UV-A (365 nm), the ACGIH recommends a TLV of 2.7 x 105 J m^{-2} for work days up to 8 hours; for periods less than 16.7 minutes, UV-A radiant exposure to the eye should be less than 1.0 x 104 J m^{-2}. For UV-C (254 nm), ACGIH recommends a cumulative limit of 6.0 x 101 J m^{-2} for work days up to 8 hours. This publication provides formulas to calculate time duration for acute exposure based on wavelength, as well as for ozone exposure (see the previous question "How do I properly/safely measure UV and verify its effectiveness").

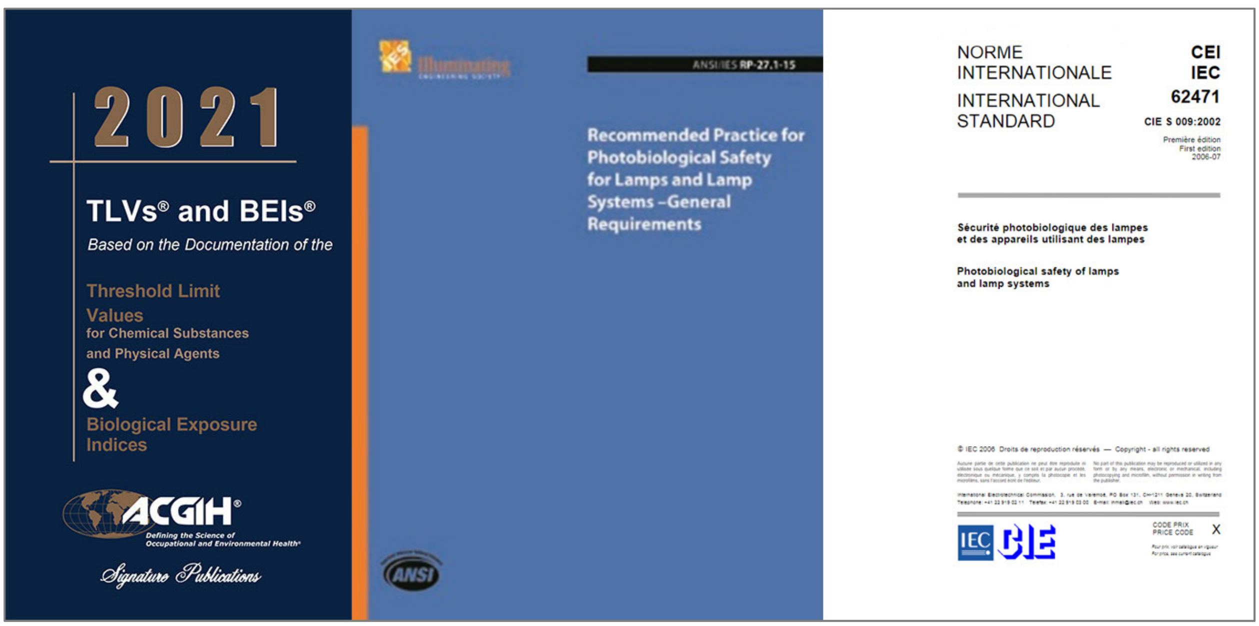


Figure 9. Standards and recommended practices relevant to UV products

The Illuminating Engineering Society's Photobiology Committee developed the ANSI/IES RP-27 series to address recommended practice for reducing the likelihood of photobiological damage from lamps and lamp systems (ANSI/IES 2015). In addition to risks from ultraviolet technologies, these publications address risks from broadband sources such as blue light hazard, aphakic hazard, and burn hazard. These publications reference the aforementioned ACGIH exposure recommendations in regards to ultraviolet exposure. Publication RP-27.3 also establishes risk category lamp classifications. Exempt products are defined as those that do not provide an actinic hazard within an 8-hour work day, nor UV-A hazard within 16.7 minutes. Low-risk products are defined as those that do not pose an actinic hazard within 2.8 hours, or those generating a UV-A hazard within 5 minutes.

The International Electrotechnical Commission (IEC) and the International Commission on Illumination (CIE) have also developed similar guidance for photobiological safety (IEC 62471 – Photobiological safety of lamps and lamp systems); compliance is required for products in the European Union (IEC 2006).

As of late 2020, energy codes in North America do not address UV and other radiative disinfection strategies. At the moment these technologies are neither included nor explicitly exempted from energy code. However, committees in charge of definitive interpretation are in the process of addressing present ambiguity. These disinfection technologies are expected to be formally exempted from energy code in North America. Germicidal lamps are exempt from efficacy standards in the State of California (Title 20).

Utility providers are considering whether to limit or, conversely, incentivize ultraviolet technologies. Both the Tennessee Valley Authority[4] and Phoenix, Arizona-based SRP[5] have announced that they will incentivize use of UV technologies in HVAC systems.

[4] https://www.tva.com/newsroom/press-releases/tva-offers-incentives-for-virus-killing-uv-technology
[5] https://media.srpnet.com/srp-offers-ultraviolet-germicidal-irradiation-business-rebate/

How can I accurately estimate the potential damage that a UV system will cause to room surfaces and objects over time?

The photon energy of UV radiation changes the chemical bonds (especially the carbon-carbon double bonds) of pigments, dyes, and many materials. With long-term exposure (months or years), materials may fade, develop distorted color, or may become brittle. ASTM International (formerly known as the American Society for Testing and Materials) has developed a blue wool scale for colorfastness (Figure 10), but this has been aimed at sun exposure rather than shorter wavelengths such as UV-C.

Figure 10. Blue wool test of colorfastness at a UV-A installation

If a space is being newly built, select materials and finishes that contain UV inhibitors such as ones designed for outdoor exposure. While UV-protective additives for many synthetic materials are available, these cannot be added retroactively to pre-existing room materials. Inorganic materials such as tile are non-reactive to UV, but carpets, fabric, dyes, wood finishes, and hydrocarbon plastics will be damaged by UV exposure. Houseplants may also be harmed by sufficient UV-C exposure, so move them away from exposure.

What are the energy implications of UV disinfection technology?

Electric energy efficiency, or more accurately disinfection efficacy, is an important consideration when deciding whether to use UV disinfection technology. Such decisions are particularly difficult for a variety of reasons. The radiative efficacy of any technology must be quantified in terms of its benefit per watt-hour. Watt-hours of operation are easy to measure; if the expected benefits among UV disinfection technologies were the same, their radiative efficacies would be easy to compare. However, the actual benefit provided by a UV disinfection technology is nearly impossible to quantify.

The benefits of a UV disinfection technology depend upon successful inactivation of a pathogen. If no pathogen is likely to be present, the energy supplied to the UV disinfection technology is wasted. It is currently impossible to measure the presence or absence of pathogens in real-time. Therefore, at the most basic level, one can never know with certainty whether the operation of the UV disinfection technology wasted electric energy.

Setting aside the possible presence or the absence of the pathogen, it remains difficult to compare UV disinfection technologies in terms of their benefits. This is because of differing (a) radiative dose for inactivation among pathogens (virus, bacterium, or fungus); (b) mode for inactivation (direct damage to DNA/RNA or indirect damage though reactive oxygen species); (c) desired level of daily inactivation (e.g., 90%, 99% or 99.99%); and (d) medium (air or surfaces). To avoid wasted electric energy, the engineer or specifier should document the target pathogen, the mode of inactivation, the inactivation criterion, and the medium where the UV disinfection should be applied. Only after documenting expected outcomes can the most cost-effective and efficacious UV disinfection technology be assessed.

The presence or absence of the target pathogen must also be addressed to evaluate radiative efficacy. *Lighting Answers* proposes the following three levels of risk that must be set by the client in cooperation with the specifying engineer: high, medium, or low. Based upon the perceived risk and the engineering specifications stated above, the radiative efficacy of a UV disinfection technology intervention and operation can be more accurately assessed.

High risk is defined as:

1. Particularly lethal pathogen (e.g., COVID-19)
2. Likely to be communicated among occupants
3. A high turnover of people (crowded public spaces)

For these spaces, concern about energy is outweighed by the societal risks. UV disinfection technology should be operated when the space is occupied (when the product can be used without exceeding exposure limits) and for necessary periods when the space is unoccupied for the deactivation of both airborne and surface pathogens.

Medium risk is defined as:

1. Possibly lethal (e.g., tuberculosis)
2. Can be readily communicated among occupants

3. A high turnover of people (public or semi-public spaces)

For these spaces, energy is of some concern, and the operation of the UV disinfection technology should be focused on times of occupancy, for deactivation of airborne and surface pathogens, and when people are present in a space. As an alternative for only surface disinfection, the use of UV disinfection technologies that cannot be operated without exceeding exposure limits when a space is occupied can be considered for use when a space is unoccupied. However, these two strategies should not be used in tandem, to avoid a waste of electric energy.

Low risk is defined as:

1. Unlikely to be lethal but potentially dangerous for vulnerable populations (e.g., hospital patients)
2. Difficult to communicate among occupants as long as routine hygiene is carried out (e.g., public bathrooms)
3. Stable occupant profile who are not ill (e.g., commercial offices without public access)

UV disinfection technologies should be used as a second-level intervention, augmenting existing cleaning procedures in specific areas that might be a source of person-to-person contamination (e.g., sink or wet counter).

The use of UV disinfection technology typically augments other measures to combat pathogens in the air and on surfaces. It is rarely, if ever, used as a standalone measure. It should not replace such efforts as increased air circulation or improved air filtration; or the use of chemical agents to kill or deactivate pathogens on surfaces. Therefore, an accurate energy and life-cycle cost analysis must also consider these other efforts as well.

Appendix A: Testing Methodology

The LRC selected UV disinfection products that are readily available, least expensive, new to the market, and/or tend to be used in commercial settings. Gonioradiometric testing was performed in a light-controlled laboratory with temperature maintained at 25°C ± 2°C. Product samples were operated until output stabilized. For products with an integral passive infrared (PIR) occupancy sensor, the sensor was defeated by physical covering. Except as noted, the radiometric intensity distribution of each fixture was measured using a 2-axis goniometer arranged in a type C configuration and attached to one end of a 2.50 m bar photometer. Different photodiode detectors were used to measure the different spectral regions of product output: SiC for UV-C, GaP for UV-A and short-wavelength visible light, and filtered Si for visible light. The angular limits and increments of the goniometric measurements were adjusted for each product to capture the full range of radiant flux output, typically gamma angles in 4° increments from at least 0° to 90° and C angles in 22.5° increments from 0° to 337.5°. Electrical power characteristics were measured immediately before or after gonioradiometric measurements using a digital sampling power meter (WT210, Yokogawa, Sugar Land, TX).

Spectral UV measurements (200 nm to 430 nm) were performed using an irradiance-calibrated UV spectrometer (BTS2048-UV-S, Gigahertz Optik, Türkenfeld, Germany) at a known distance (2 m, except as noted). For products with visible or white output (380 nm to 780 nm), relative spectral measurements were converted to absolute using illuminance measurements from a calibrated illuminance meter at a 2-meter distance.

Ozone measurements were performed in an isolated room with an exhaust fan. A plywood chamber (47-inch x 24-inch x 18-inch) was built with multiple small air intakes and an exhaust port with a 6 inch variable speed fan and a wireless anemometer to measure discharge air velocity remotely. An ozone meter (Model 200, EOZ O3, Aeroqual, Auckland, New Zealand) sampled air in the exhaust port. Each UV product was operated for 30 minutes for three fan speeds (200, 300, 400 cubic feet per minute, CFM). Ozone concentration at each fan speed was then used to calculate ozone output (in units of ozone grams per hour).

The ozone output of several UV products was too low for the ozone meter to reliably detect (<0.05 ppm), but the researchers were able to smell ozone. The LRC operated those sources in an odor-neutral acrylic sealed enclosure for 30 minutes with the ozone sensor. At the end of 30 minutes, the lid was lifted and two researchers recorded whether they could smell ozone.

No ozone measurements were performed on products incapable of producing UV emissions at wavelengths shorter than 240 nm (confirmed by spectral measurements in some cases) and without other ozone-producing technology. Additional methodologies for specialized product samples are described below.

Ceiling or Wall-mounted D (Ceiling-mounted 5-inch UV-C device)
Due to very low output, gonioradiometric measurements were performed at a 30 cm distance on the bar photometer. This product underwent additional testing for stabilization time and possible corrections for operating it horizontally on the gonioradiometer. It was

operated in its intended orientation (horizontal, to simulate ceiling-mount condition) for 24 hours, and relative UV output was monitored over time. These data were used to adjust the gonioradiometric measurements to represent stable, horizontal operation.

Portable Room Sanitizer B (pulse xenon flashing module)
This product delivers a 3-millisecond pulse every 6 seconds. To enable goniometric measurement, the movement of the goniometer was synchronized with these pulses; one pulse for each movement. Detector photocurrent was amplified and converted to a voltage signal and then low-pass filtered by a resistor capacitor (RC) circuit with a time constant of 0.1 second. A digital multimeter (34401A, Agilent Technologies, Santa Clara, CA) was used with remote computer control then recorded the waveform at a sampling rate of 100 Hz. Digital waveform pulses were integrated over time and calibrated to a corresponding spectrometer reading. Spectral data were obtained by operating the spectrometer in manual exposure mode with an exposure time of 4 seconds. The spectrometer was manually triggered to capture a single flash. Four repeated measurements producing nearly identical readings indicated that the entire flash duration was completely captured (Figure A-1). The electrical power demand and associated power characteristics of the flashing product varied greatly over the flash period from a few watts to over 100 watts. A time-averaged power demand was calculated by measuring the input electrical energy (Wh) over a 10-minute period and dividing by the period. Due to their great variability and measurement complexity, other power quality metrics were not measured.

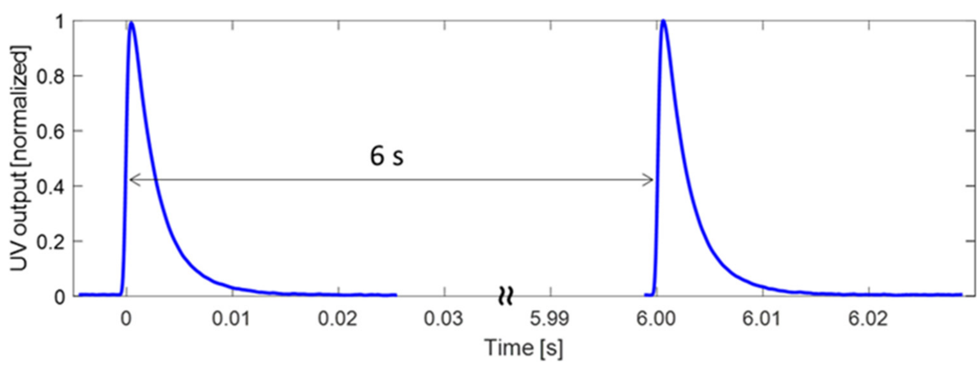


Figure A-1. For the pulse xenon product, power demand and UV output varied with time

UV Wand Measurements
Near-field radiometry was employed to measure the UV output of the wands and to calculate disinfection times because they are intended to be used at close distances relative to their size. Products were mounted horizontally over a table on which a grid was drawn with 10 cm spacing. A UV-C detector (GaN photodiode with PTFE diffuser) was manually moved over the grid in 5 cm increments and irradiance recorded at each position. Wand "A" included instructions stating a distance of 3 to 5 cm should be maintained when using, so a vertical measurement distance of 4 cm was chosen. Instructions for wand "B" did not mention a distance, but because of its larger size and LED spacing a distance of 15 cm was added to the near-field measurements. UV spectrometer measurements were taken directly below each wand at distances of 4 cm and 15 cm to calibrate the photodiode detector readings. The 4 AAA batteries of Wand "A" were removed and the product was powered by

a 6.00 V dc power supply to maintain output constant during the measurement period. The size of the measurement grid extended to where no further UV was detected.

Wand A (LPD Hg): This battery-powered product underwent additional testing for battery discharge duration. The researcher installed four new AAA alkaline batteries (Energizer Industrial LR03 batteries, expiration date 12-2029) and recorded the UV output every 10 seconds until the batteries were fully expended (129 minutes).

Because this LPD Hg product has such low output, this product was excluded from ozone measurements; this was not within the sensitivity range of the ozone meter.

Wand B (LED): This product has rechargeable batteries that underwent additional testing for discharge duration. The researcher charged the device until the green indicator light illuminated and then continued to charge for an additional 24 hours. This product has an automatic shutoff feature after approximately 5 minutes of operation. To enable battery testing, the researcher soldered wires to the push button switch terminals that turn the UV output on and off and connected these wires to a computer-controlled relay. The computer data acquisition system (LabView version 2010, National Instruments, Austin, TX) was programmed to switch the product off and then back on again with a 1-second pause after every 4 minutes of operation. The battery was expended after 75 minutes.

Because this product uses LEDs, this product was excluded from ozone measurements, as it does not emit wavelengths shorter than 240 nm.

UV-C Dose Cards

Dose cards were exposed to three different UV sources (low-pressure mercury UV-C, LED UV-C, and LED UV-A) at various irradiance levels. Table A-1 summarizes the test conditions. For UV-C sources, a software program was written that used a UV sensor to monitor the precise dose delivered to the card being tested. The cards were exposed to a total of 1300 J m^{-2} with increments of 100 J m^{-2} between observations. After each 100 J m^{-2} exposure, the chromaticity of the indicating region of the dose card was measured (CS-2000A spectroradiometer, Konica Minolta, Tokyo, Japan) while being illuminated by an incandescent lamp. These data were subsequently compared to the chromaticity of the reference color patches corresponding to 500 J m^{-2} and 1000 J m^{-2}.

Table A-1. Summary of the rates used to expose the UV-C dose cards

Source	Average Rate W m^{-2}
LPD Hg	0.29
	3.9
	27
UV-C LED*	0.25
	2.5

**The UV-C LED did not produce enough output to make a 25 W m^{-2} exposure rate practical.*

The sensitivity of the UV-C dose cards to UV-A radiation was also tested. Only one card was used to evaluate the UV-A sensitivity; it was placed approximately 4 cm from the face of an LED-based UV-A emitter producing an irradiance of 270 W m^{-2} on the card. The card was exposed to the UV-A radiation for two 30-minute periods, and the chromaticity of the indicating region of the card was measured after each exposure period.

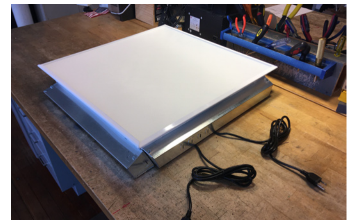
Appendix B: Test Results

Appendix B includes test results for three hybrid products (UV + visible light), four dedicated ceiling- and wall-mounted UV products, two portable whole-room sanitizers, a portable air purifier, and two UV wand products. Appendix B also includes results from testing a UV measurement card product.

Data Sheet

Hybrid A

Description: 2×2 lensed troffer
Source: LED, both UV-A disinfection and white-light modes



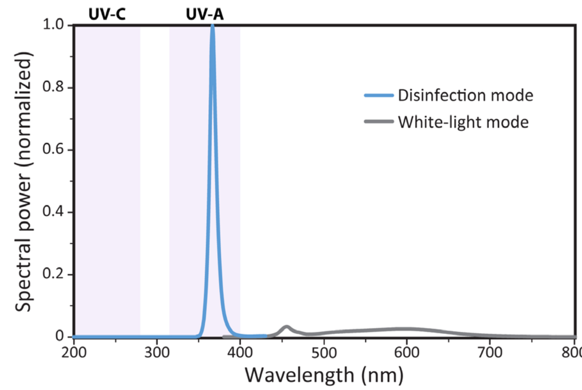
Manufacturer-reported data

Power: Not provided (engineering sample)
Life: Driver >10 y continuous operation
Instructions for operation: Leave UV-A on for continuous bacterial reduction

LRC test results

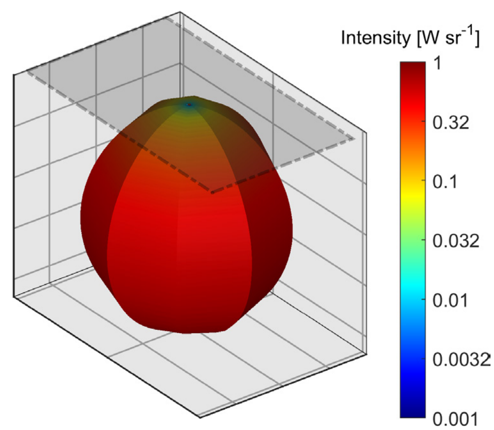
Peak wavelength, CCT: 365 nm (UV-A), 3975 K (white light)
Ozone: Not tested
Controls: UV-A designed to be left on for extended durations, can be switched separately from white light
Voltage: 120 V (UV-A), 121 V (white light)
Current: 0.091 A (UV-A), 0.215 A (white light)
Power factor: 0.95 (UV-A), 1.00 (white light)
Current THD: 12% (UV-A), 5% (white light)
Input power: 10.3 W (UV-A), 25.9 W (white light)
Radiant power output: 1.82 W (UV-A)

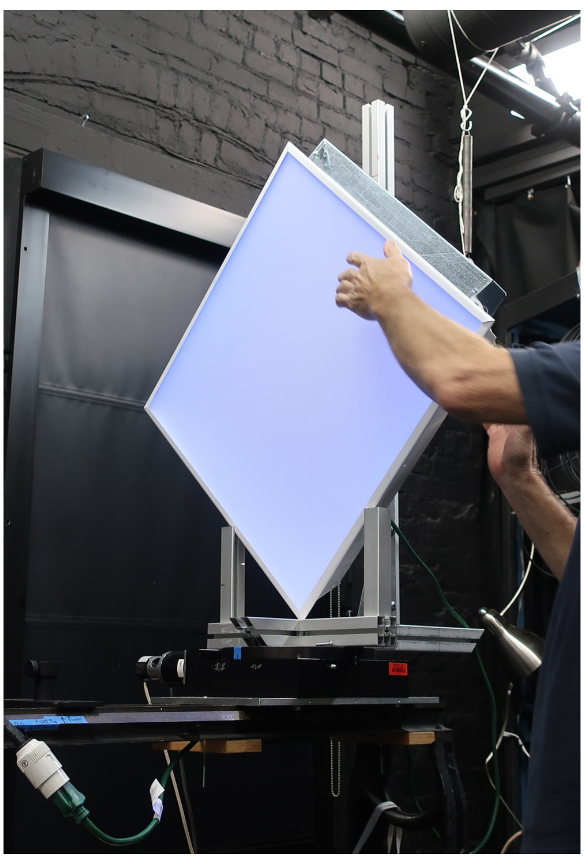
Spectral power distribution

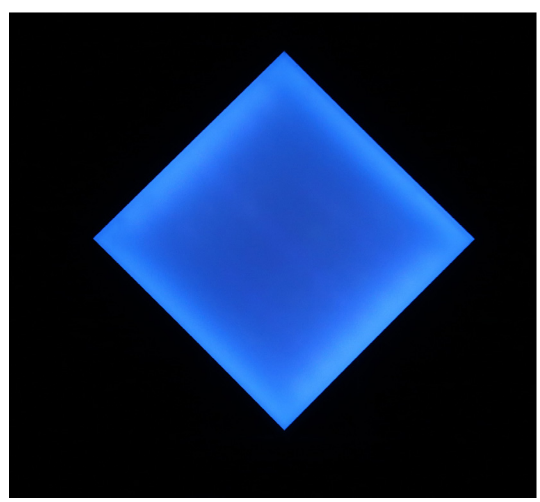


Intensity distribution

UV-A intensity (W sr^{-1})



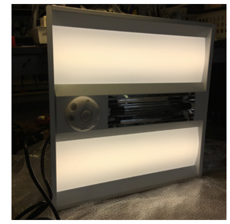




Data Sheet

Hybrid B

Description: 2×2 basket-type troffer with integral motion sensor
Source: Low pressure discharge Hg (UV-C disinfection mode), LED (white-light mode)



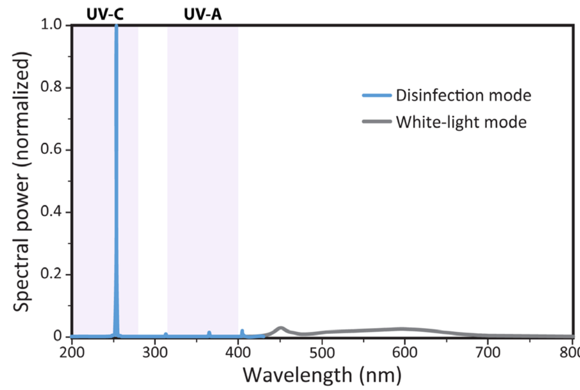
Manufacturer-reported data

Power: 50 W including UV-C (nominal 10 W) and white-light modes
Life: 9000 h or 1 y
Instructions for operation: Indicator light warns when UV-C lamp is energized

LRC test results

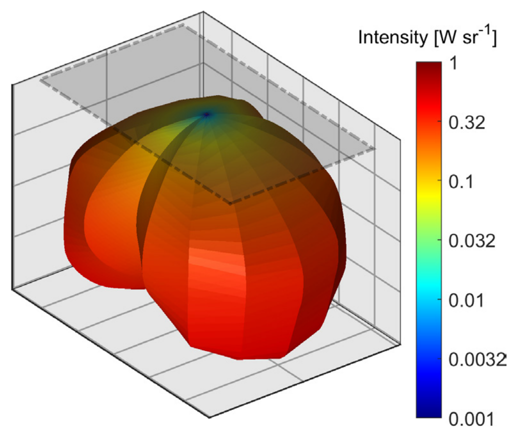
Peak wavelength, CCT: 254 nm (UV-C), 4020 K (white light)
Ozone: None detected at <0.01 ppm, but researchers could smell trace amounts
Controls: Integral motion sensor uses both ultrasonic and infrared to control UV-C channel
Voltage: 120 V (UV-C), 121 V (white light)
Current: 0.116 A (UV-C), 0.225 A (white light)
Power factor: 0.99 (UV-C), 1.00 (white light)
Current THD: <1% (UV-C), <1% (white light)
Input power: 13.7 W (UV-C), 26.8 W (white light)
Radiant power output: 1.29 W (UV-C)

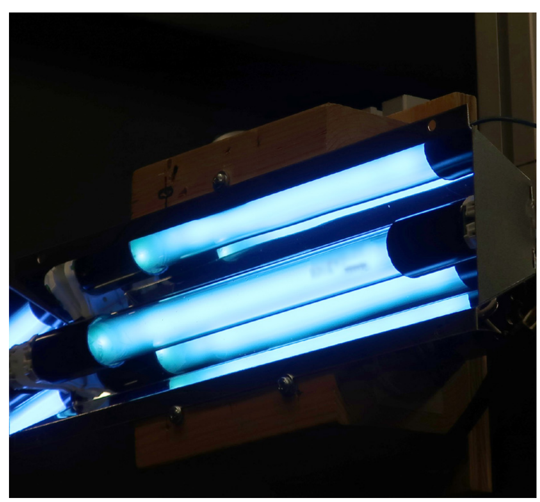
Spectral power distribution



Intensity distribution

UV-C intensity (W sr^{-1})

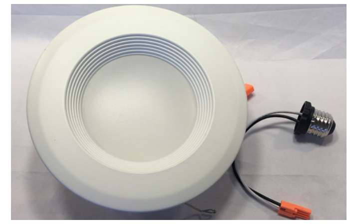




Data Sheet

Hybrid C

Description: 7.5-in (outer diameter) recessed downlight retrofit kit, rated for wet location
Source: LED, both visible violet-light disinfection or white-light modes (cannot operate concurrently)



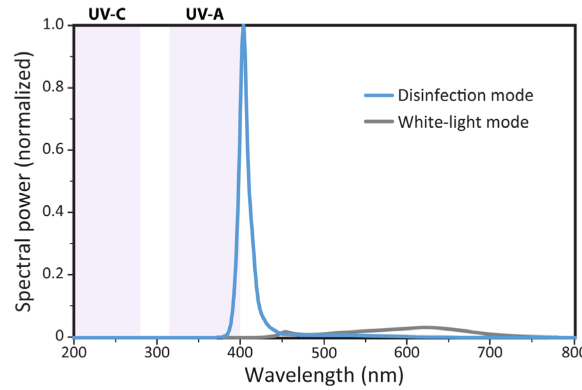
Manufacturer-reported data

Power: 13 W (white-light or visible violet-light disinfection modes not specified)
Life: Up to 50,000 h
Instructions for operation: Install at heights up to 9 ft. Double-click wall switch to activate violet-light disinfection mode; intended to address bacteria, mold, and fungi on surfaces (but neither viruses nor air disinfection). Can be used continuously around people and pets.

LRC test results

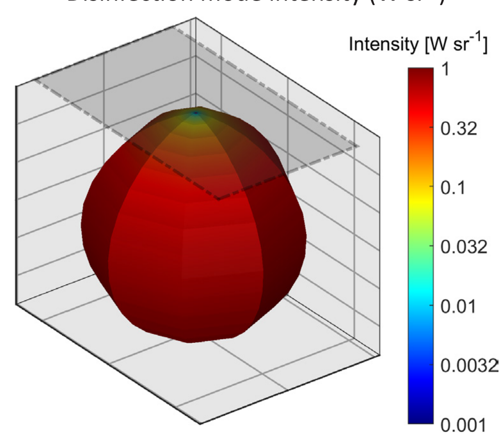
Peak wavelength: 405 nm (disinfection mode)
Produces ozone: Not tested
Controls: Double-click of wall switch diverts power to disinfection channel
Voltage: 120 V (both disinfection and white light)
Current: 0.117 A (disinfection), 0.105 A (white light)
Power factor: 0.99 (disinfection), 0.98 A (white light)
Voltage THD: 0.06% (disinfection), 0.07% (white light)
Current THD: 13% (disinfection), 14% (white light)
Input power: 13.8 W (disinfection), 12.5 W (white light)
Radiant power output: 2.49 W (disinfection)

Spectral power distribution



Intensity distribution

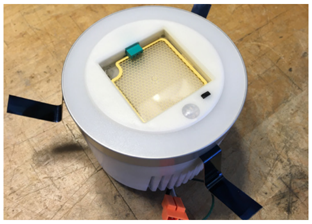
Disinfection mode intensity (W sr^{-1})



Data Sheet

Ceiling- or wall-mounted A

Description: 4-in recessed downlight with integral motion sensor
Source: Krypton chlorine excimer



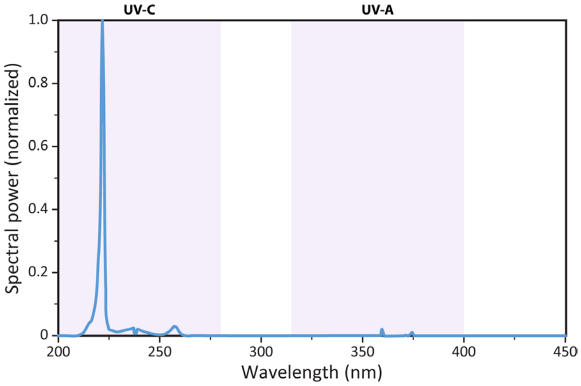
Manufacturer-reported data

Power: Engineering sample with input power of 10 W far UV-C
Life: > 3000 h (excimer)
Instructions for operation: Suitable for 8 h of daily exposure at 3-ft distance. Do not install in a dwelling. Commercial version available with programmable integral occupancy sensor, and for variable duty cycles.

LRC test results

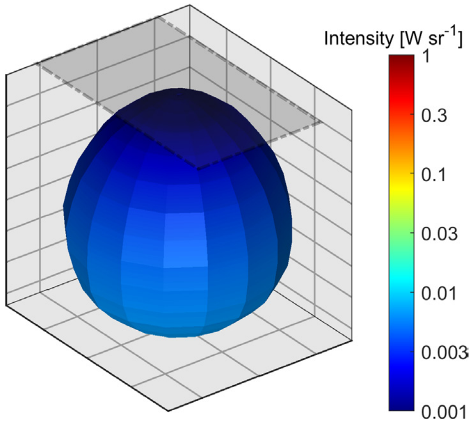
Peak wavelength: 222 nm
Ozone: None detected at <0.01 ppm
Controls: Disabled for engineering sample
Voltage: 120 V
Current: 0.177 A
Power factor: 0.48
Current THD: 177%
Input power: 10.2 W
Radiant power output: 0.016 W (UV-C)
Comment: Commercial versions may use a filter to limit wavelengths >230 nm

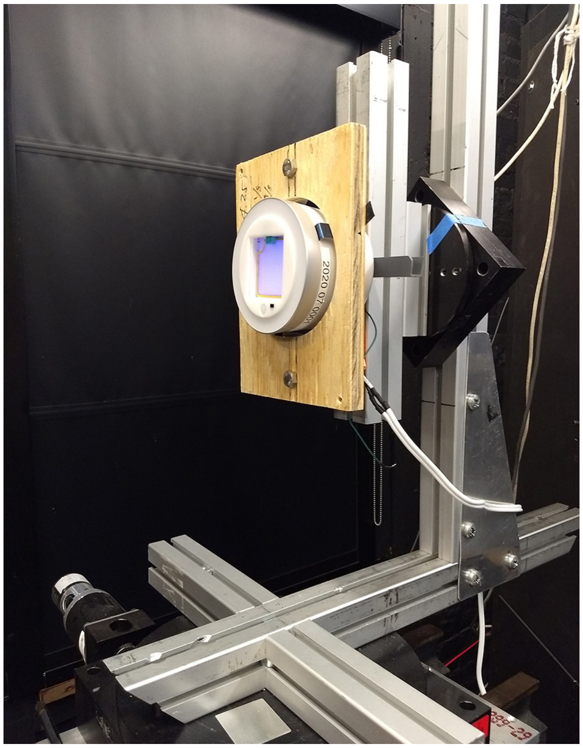
Spectral power distribution



Intensity distribution

UV-C intensity (W sr^{-1})





Data Sheet

Ceiling- or wall-mounted B

Description: Discharge source intended for integration into a disinfection luminaire
Source: Krypton chlorine excimer

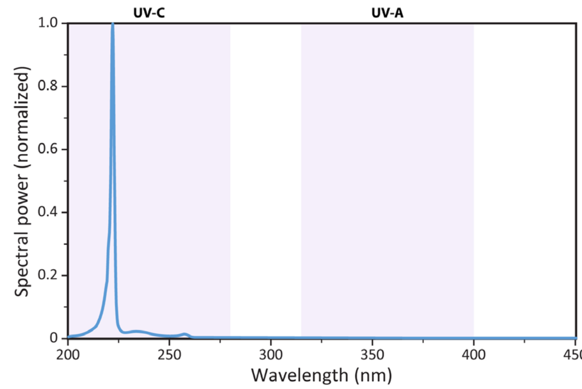
Manufacturer-reported data

Power: 40 W
Life: Note specified
Instructions for operation: Intended for manufacturer integration into disinfection products. Preliminary literature indicates suitable for occupant exposure.

LRC test results

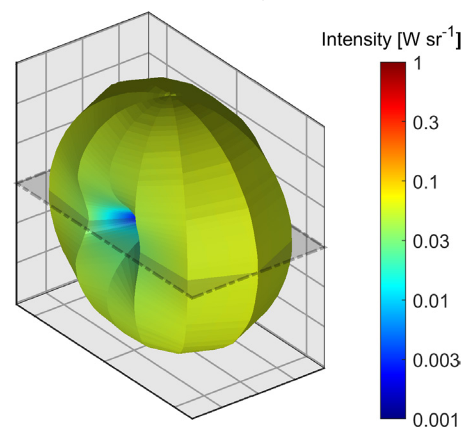
Peak wavelength: 222 nm
Ozone: None detected at <0.01 ppm, but researchers could smell trace amounts
Controls: Switch on power supply
Voltage: 120 V
Current: 0.605 A
Power factor: 0.64
Current THD: 124%
Input power: 46.2 W
Radiant power output: 0.59 W (UV-C)
Comment: Commercial versions may use a filter to limit wavelengths >230 nm.

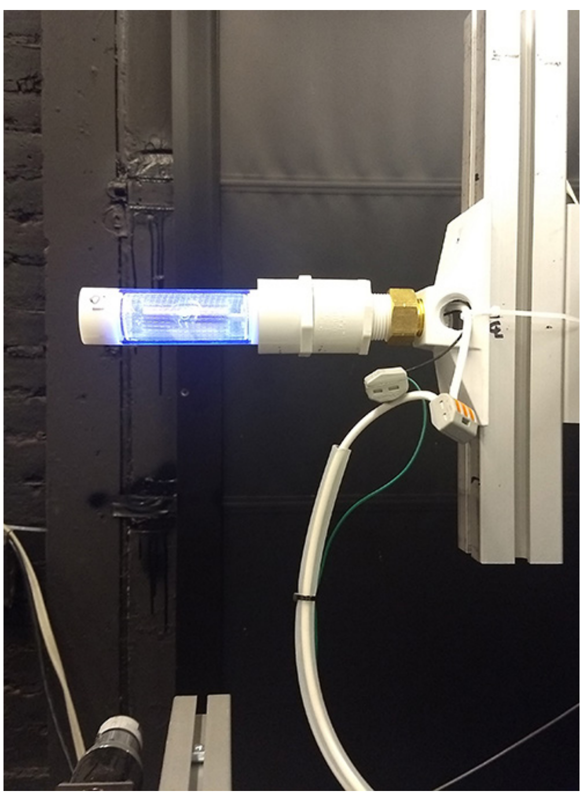
Spectral power distribution

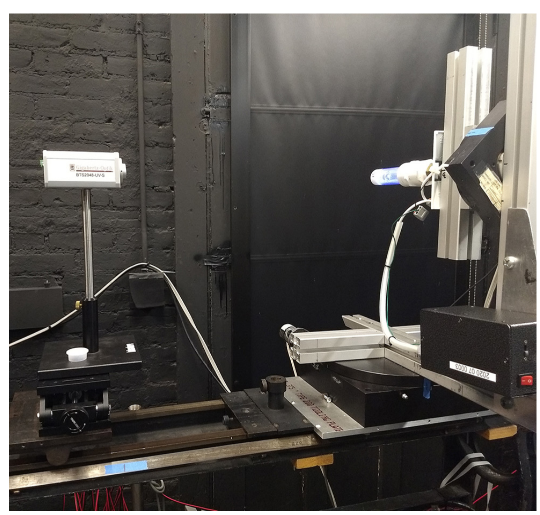


Intensity distribution

UV-C intensity (W sr^{-1})





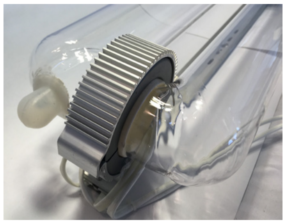


Data Sheet

Ceiling- or wall-mounted C

Description: 21-in long electrodeless low pressure discharge Hg source intended for integration into a disinfection luminaire

Source: Low pressure discharge Hg



Manufacturer-reported data

Power: 300 W

Life: 100,000 h

Instructions for operation: Do not touch bulb. Use in dry location. Designed for mounting into suspended ceiling grids or directly on ceilings/walls. Another model is available for portable use. Only use in evacuated spaces free of any people or animals.

LRC test results

Peak wavelength: 254 nm

Ozone: Yes

Controls: None included

Voltage: 119 V

Current: 2.41 A

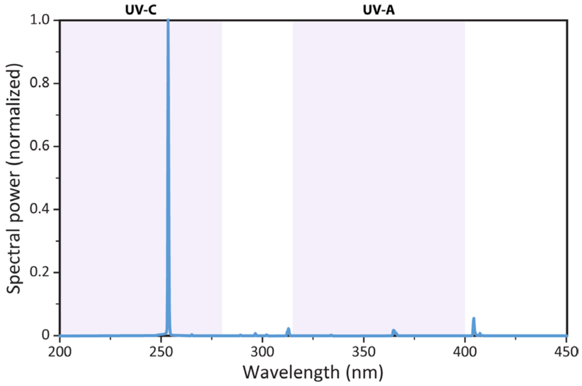
Power factor: 1.00

Current THD: 2%

Input power: 288 W

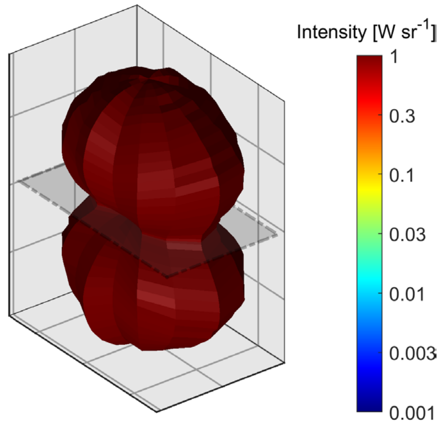
Radiant power output: 75.9 W (UV-C)

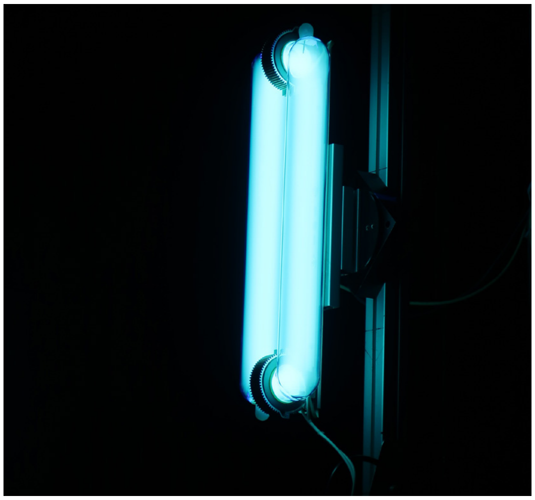
Spectral power distribution



Intensity distribution

UV-C intensity (W sr^{-1})

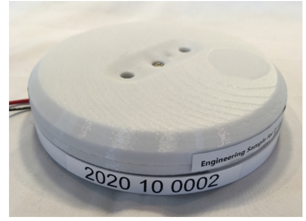




Data Sheet

Ceiling- or wall-mounted D

Description: Compact, surface-mounted device intended for continuous air disinfection
Source: UV-C LED



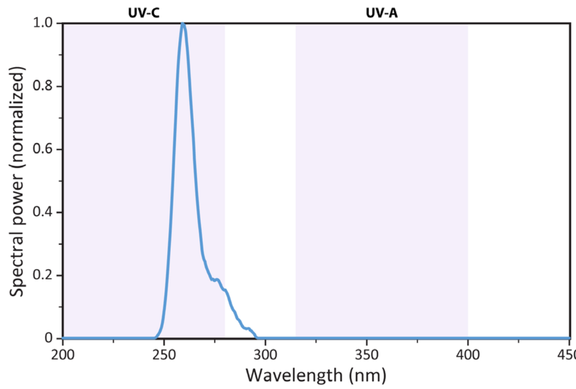
Manufacturer-reported data

Power: Not specified (engineering sample)
Life: 1 y
Instructions for operation: At 10-ft mounting height, expected to inactivate aerosolized coronavirus in <6 h. Below the daily exposure limits specified by IEC 62471 (2006).

LRC test results

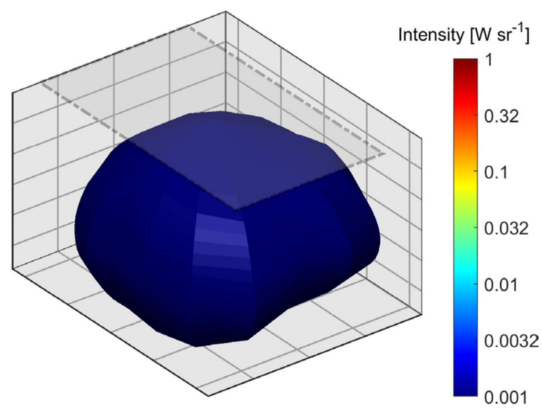
Peak wavelength: 254 nm
Ozone: None detected at <0.01 ppm
Controls: None included
Voltage: 121 V
Current: 0.057 A
Power factor: 1.00
Current THD: 198%
Input power: 2.77 W
Radiant power output: 0.00095 W (UV-C)
Comments: Very low output requires continuous use to achieve disinfection. Stabilizes output after 90 min at 73% lower irradiance than initial (1 min) output.

Spectral power distribution

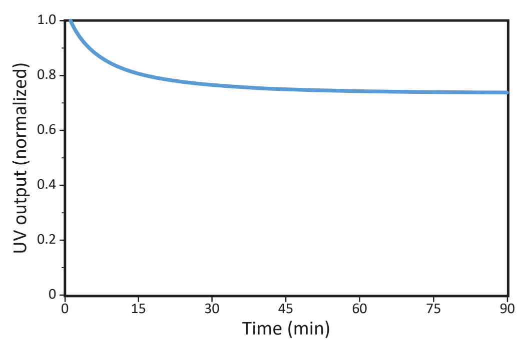


Intensity distribution

UV-C intensity (W sr^{-1})



Stabilization over time



Data Sheet

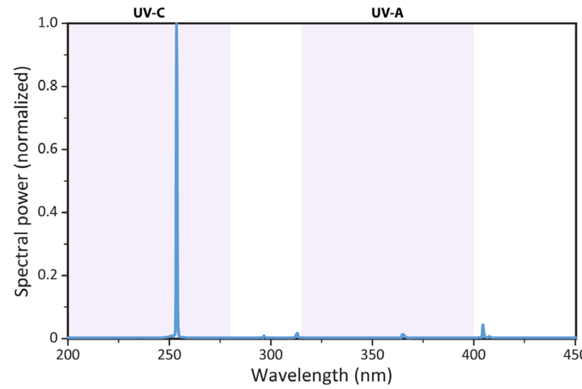
Portable room sanitizer A

Description: 21-in tower with integral motion sensor and timer
Source: Low pressure discharge Hg, single-ended biaxial lamp

Manufacturer-reported data

Power: 60 W
Life: 9000 h
Instructions for operation: Close all doors and windows. Select cycle duration (15/30/45/60 min) and depart room within 10 s. Post a warning sign on the door while in use. Do not allow exposure with skin, animals, or plants. Do not expose artwork. Never look at UV-C light while in use. Allow lamp to cool for 10 min after disinfection. Bulb should be wiped off quarterly with ethanol.

Spectral power distribution

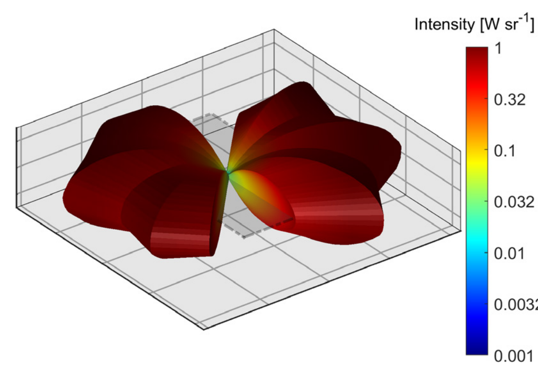


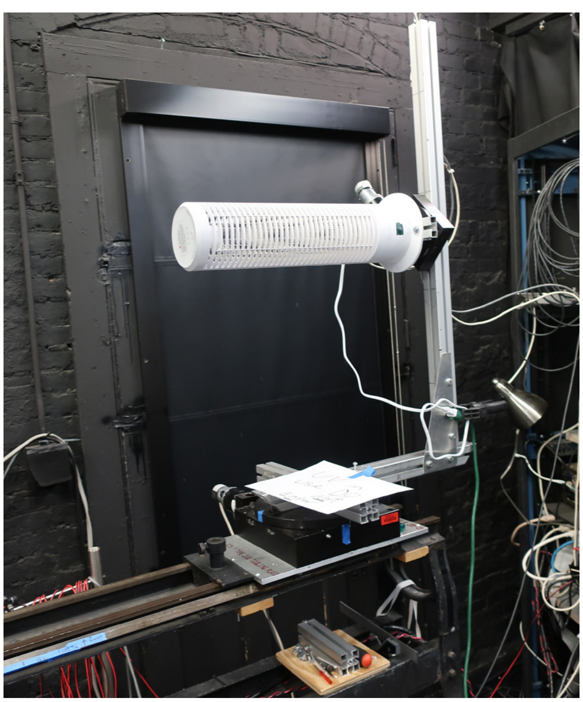
LRC test results

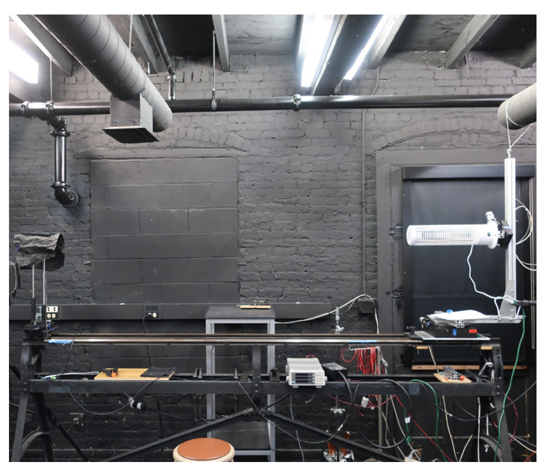
Peak wavelength: 254 nm
Ozone: Yes
Controls: Motion sensor and timer
Voltage: 120 V
Current: 0.658 A
Power factor: 0.84
Current THD: 113%
Input power: 66.3 W
Radiant power output: 4.72 W (UV-C)

Intensity distribution

UV-C intensity (W sr^{-1})



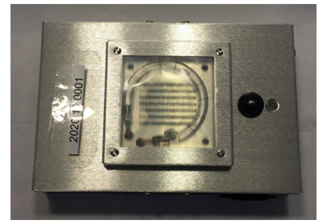




Data Sheet

Portable room sanitizer B

Description: Broadband flashing module intended for mounting on tripod (for portable operation) or building surfaces
Source: Pulsed xenon



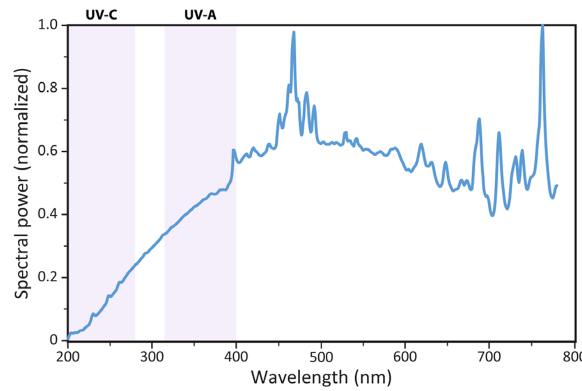
Manufacturer-reported data

Power: 25 W
Life: 9.1 y at 1 h per day (3322 h)
Instructions for operation: Operate for 30 min. Do not look at the light source. Will effectively inactivate pathogens up to 4 m (~13 ft) away. For resistant pathogens use two consecutive 30-min cycles at 1 m distance, or four cycles if ceiling-mounted.

LRC test results

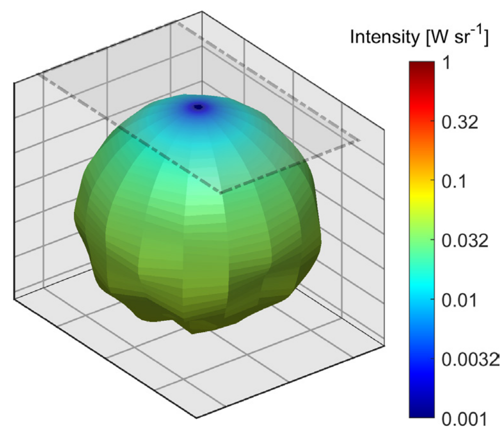
Peak wavelength: Broadband
Ozone: None detected at <0.01 ppm, but researchers could smell trace amounts
Controls: Preset timed cycle of 30 min, motion sensor override, can integrate with building management software for permanent installation
Voltage: 121 V
Current: 0.0513 A
Power factor: Not tested (variable)
Current THD: Not tested
Input power: 53.3 W (time average)
Radiant power output: 0.170 W (UV-C, time average)

Spectral power distribution

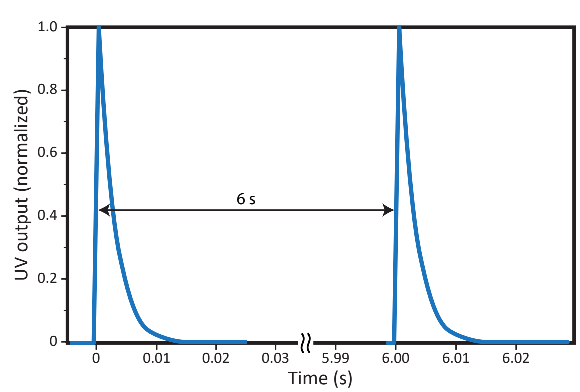


Intensity distribution

UV-C intensity (W sr^{-1})



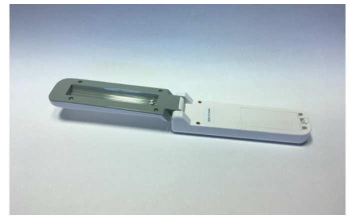
UV output over time



Data Sheet

UV wand A

Description: Portable, hand-held wand powered by four AAA batteries or USB cable
Source: Low pressure discharge Hg



Manufacturer-reported data

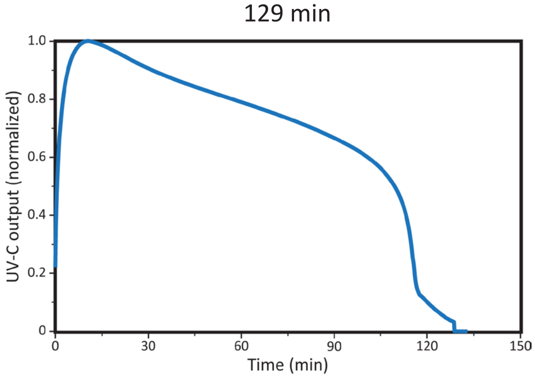
Power: 2 W
Life: Not specified
Instructions for operation: Wave wand over surface at 1.6 in (4.0 cm) distance for 30 s

LRC test results

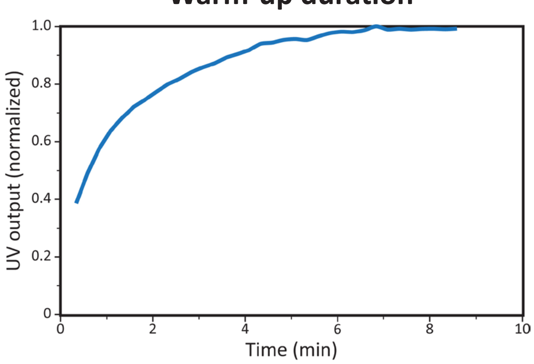
Peak wavelength: 254 nm (UV-C)
Ozone: Not tested
Warm-up time: 500 s (8.3 min), battery droops afterward
Controls: Switch on side; turns off at 82–97° tilt
UV-C dose (30 s): 17.1 J m^{-2} at 15 cm
Duration to disinfect laptop: 1.2 min
Duration to disinfect desk: 10 min
Duration to disinfect bed: 22 min
Comments: Useful for small objects
Note: Disinfection defined as 99% inactivation of viruses on surfaces (k = 0.118 m^2 J^{-1})

Battery discharge duration

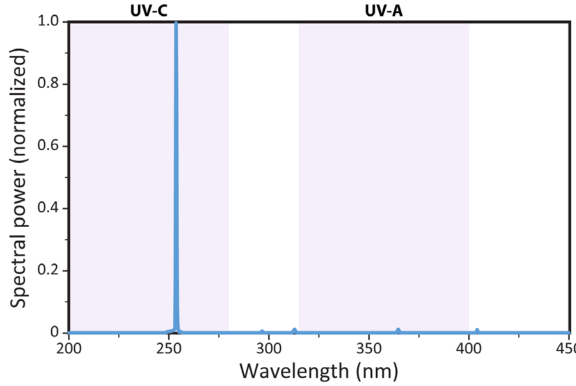
129 min



Warm-up duration

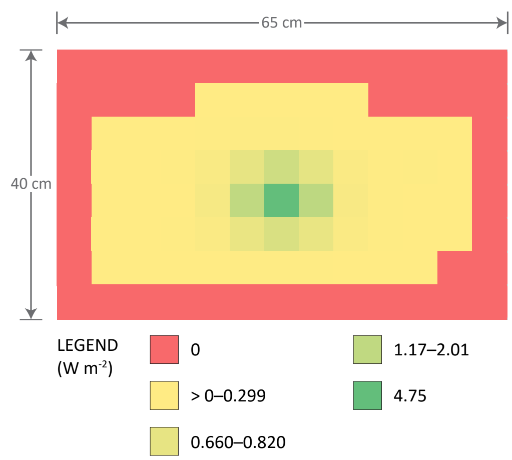


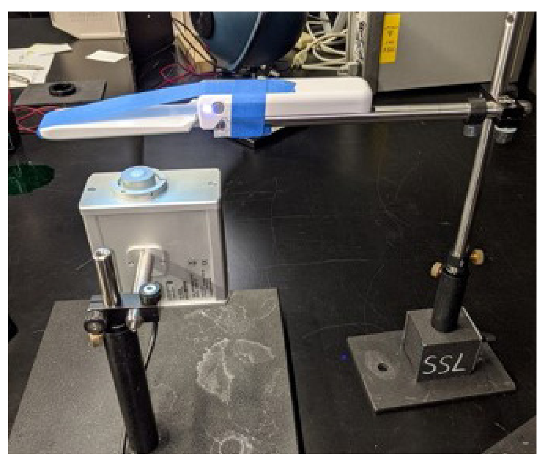
Spectral power distribution



Near-field measurements

UV-C irradiance (W m^{-2})
4-cm distance, 5-cm grid

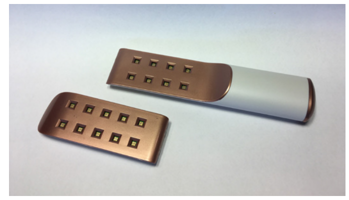




Data Sheet

UV wand B

Description: Portable, hand-held wand with detachable segment; powered rechargeable lithium battery with USB cable
Source: LED



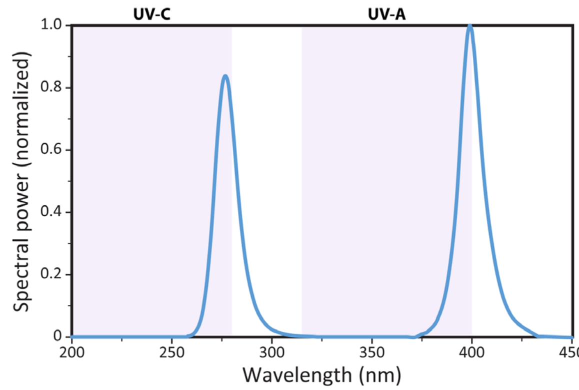
Manufacturer-reported data

Power: 7.9 W
Life: Not specified
Instructions for operation: None

LRC test results

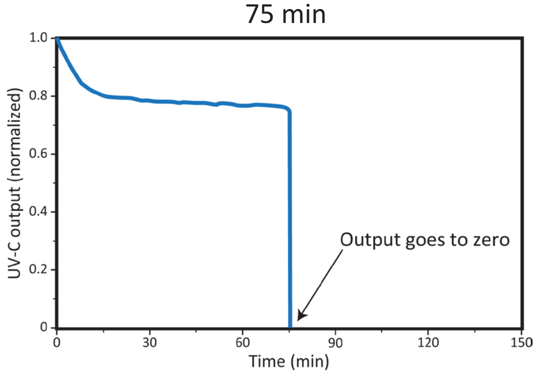
Peak wavelengths: 265 nm (UV-C), 405 nm (UV-A)
Ozone: Not tested
Warm-up time: Instant, but output reduces over time; shuts off automatically after 5 min
Controls: Switch on side; turns off at 35–38° tilt
UV-C dose (30 s): 3.6 J m^{-2} at 15 cm
Duration to disinfect laptop: 12 min
Duration to disinfect desk: 1h15min
Duration to disinfect bed: 2h39min
Comments: Apparently combines UV-C and UV-A; very low output results in limited utility
Note: Disinfection defined as 99% inactivation of viruses on surfaces (k = 0.118 m^2 J^{-1})

Spectral power distribution



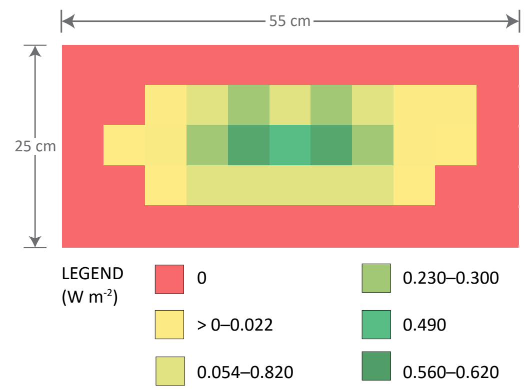
Battery discharge duration

75 min

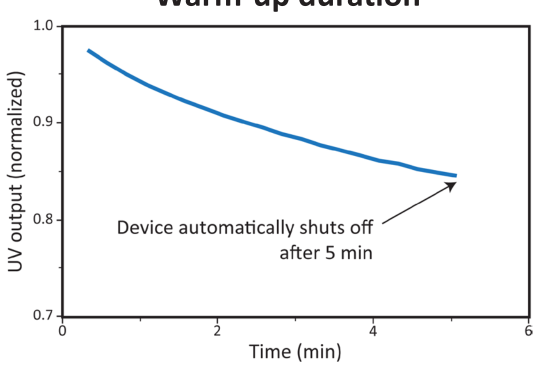


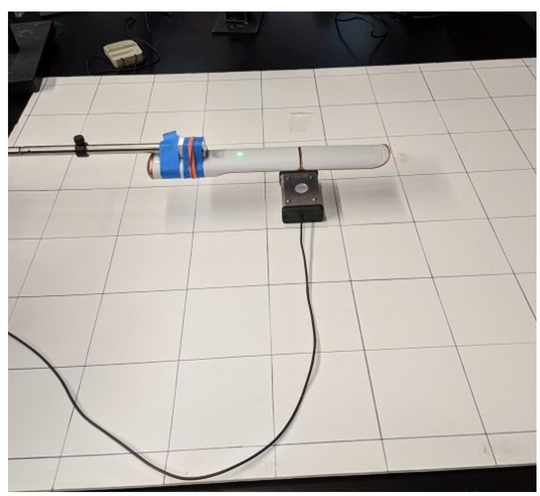
Near-field measurements

UV irradiance (W m^{-2})
4-cm distance, 5-cm grid



Warm-up duration





Data Sheet

Portable air purifier

Description: Ozone generator with auxiliary UV-C lamps
Source: Low pressure discharge Hg

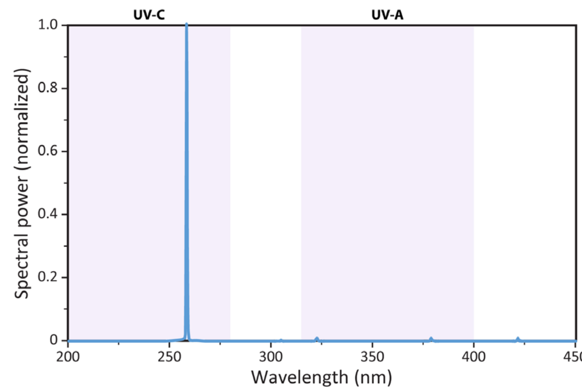
Manufacturer-reported data

Power: 70 W (including UV-C and ozone modes)
Life: 8000 h or 2 y
Instructions for operation: Treatment may be done in occupied spaces, make sure ozone is in "off" position

LRC test results

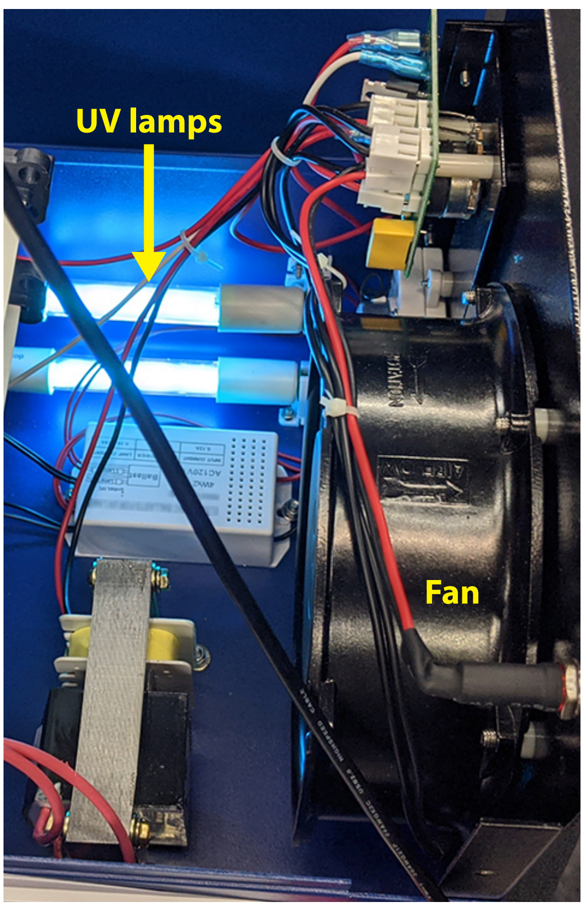
Peak wavelength: 254 nm
Ozone: Yes
Controls: Timer
Voltage: 120 V (both low and maximum)
Current: 0.421 A (low), 0.545 A (maximum)
Power factor: 0.75 (low), 0.85 (maximum)
Current THD: 17% (low), 12% (maximum)
Input power: 37.7 W (low), 55.4 W (maximum)

Spectral power distribution

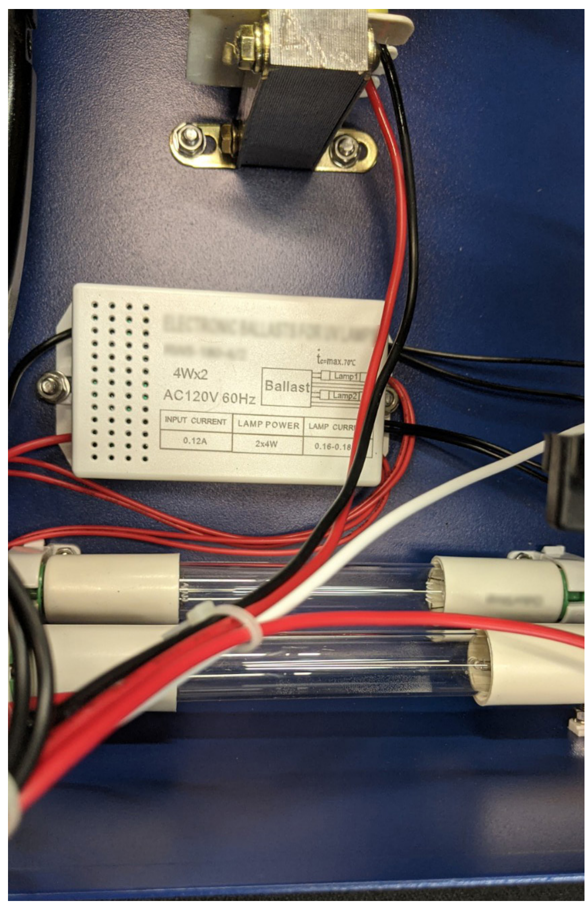


Intensity distribution

Not applicable due to enclosure



Note: LPD Hg lamps remote from central air flow; no reflector

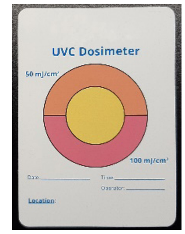


Note: Exposed components/wiring; no reflector

Data Sheet

Test card

Description: Intended to verify UV-C exposure from ultraviolet equipment, especially for medical facilities concerned about healthcare associated infections



LRC Test Results: The test cards are printed with UV-sensitive ink that shifts in color from yellow with low dose (0-250 J m^{-2}), to orange with medium dose (500 J m^{-2} ± 250), to pink with high dose (1000 J m^{-2} ± 250). The LRC objectively measured the color change of the indicators using CIE ΔE^*_{UV} where a just-noticeable color difference has a value of $\Delta E^*_{UV} = 1$ (per standard CIE Colorimetry, CIE 15:2004 3rd Edition). The color changes were measured with respect to the printed color references for medium dose and high dose. Values of ΔE^*_{UV} were repeatedly measured as the UV-C dose increased from 0 to 1300 J m^{-2}. A low pressure discharge Hg lamp was used for one set of results (Figure A). A UV LED (λ_{peak} = 275 nm) was used for a second trial using new cards, with similar results.

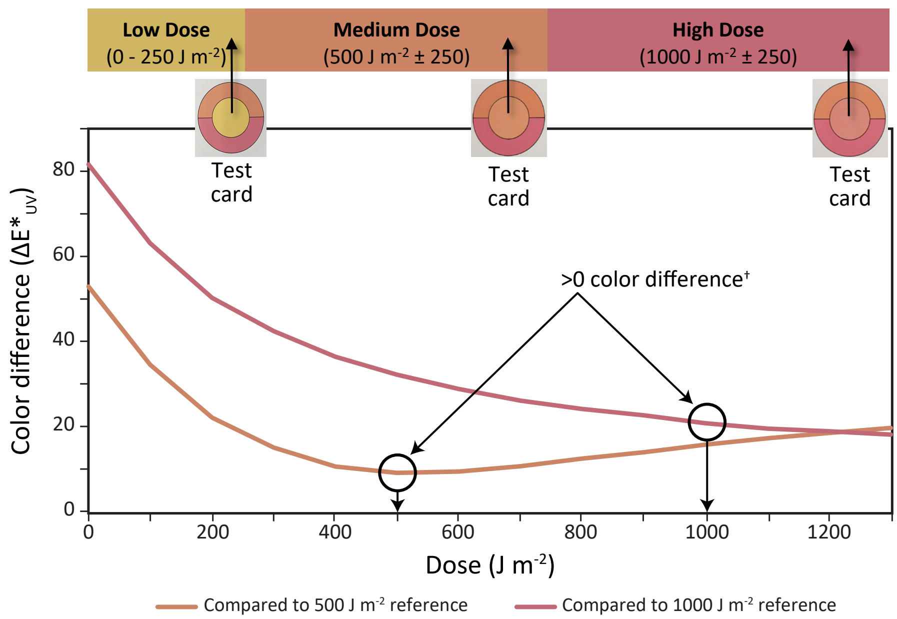


Figure A. *Color difference (ΔE^*_{UV}) compared to two test card color references (500 J m^{-2} and 1000 J m^{-2}) irradiated with UV-C (254 nm). †The design of the test card implies that there should be zero color difference at these points (a match between center reference and indicator half-rings).*

While the colors did not exactly match the reference colors at the target irradiances (see Figure A), this type of test card was successful for qualitative confirmation that UV-C was present at low, medium, and high outputs.

It should be noted that these test cards were also found to be slightly sensitive to UV-A wavelengths (Figure B). The LRC did encounter products that used UV-A instead of or in addition to UV-C. This type of test card could provide a false indication that UV-C wavelengths are in use.

The indicator dots did not retain their color shift over time. The LRC noted that the dots partially reverted to their original color 1 week after exposure; if using the cards for archival documentation, photographic evidence may need to be retained.

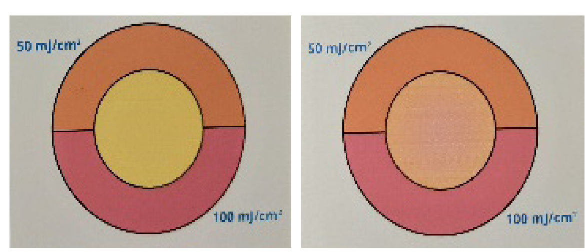


Figure B. *Card on left shows initial color (0 J m^{-2}). Card on right shows color after being exposed to 270 W m^{-2} UV-A for 60 min (a dose of 1 million J m^{-2}).*

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Glossary: Abbreviations and Definitions

AAA	standard size of 1.5 volt dry cell batteries (commonly called “triple A”)
ac	alternating current
ACGIH	American Conference of Governmental Industrial Hygienists
ASTM	American Society for Testing and Materials, former name of the organization called ASTM International
ATP	adenosine triphosphate
BEI	biological exposure indices
CEC	California Energy Commission
CFM	cubic feet per minute
CIE	International Commission on Illumination
cm	centimeter
COVID-19	coronavirus disease 2019 (illness in humans caused by SARS-CoV-2)
dc	direct current
DNA	deoxyribonucleic acid
EMI	electromagnetic interference
EPA	United States Environmental Protection Agency
Far UV-C	UV-C radiation spectra with peak wavelengths near 222 nm (colloquial designation)
g	gram
GaN	gallium nitride
GaP	gallium phosphide
GUV	germicidal ultraviolet
h	hour
HAIs	healthcare associated infections (health.gov)
HEPA	high efficiency particulate air (air filter designation)
Hg	mercury (chemical symbol)
HVAC	heating, ventilation and air conditioning
Hz	hertz
IEC	International Electrotechnical Commission
IES	Illuminating Engineering Society
in	inches
IUVA	International Ultraviolet Association
J	joule
kWh	kilowatt hour
LEA	Lighting Energy Alliance
LED	light emitting diode
LPD	low-pressure discharge, e.g., low-pressure discharge mercury lamp
LR03	IEC designation for alkaline AAA batteries
LRC	Lighting Research Center
m	meter
min	minute
ms	millisecond
NEEA	Northwest Energy Efficiency Alliance
NIST	National Institute of Standards and Technology

nm	nanometer
O3	ozone (chemical formula)
PIR	passive infrared
PM	particulate matter (also known as particle pollution) – a mixture of microscopic solid particles and liquid droplets; a subscript is used to denote the particulate size in micrometers (EPA)
ppm	parts per million
PTFE	polytetrafluoroethylene (compound commonly referred to as Teflon)
RC	resistor-capacitor electronic filter circuit
RFI	radio frequency interference
RNA	ribonucleic acid
RODAC	replicate organism detection and sampling
ROS	reactive oxygen species
s	second
SARS-CoV-2	severe acute respiratory syndrome coronavirus 2 (See COVID-19)
Si	silicon
SiC	silicon carbide
SRP	Salt River Project, a community-based, not-for-profit public power utility and the largest provider of electricity in the greater Phoenix metropolitan area
TB	tubercle bacillus (bacterium responsible for tuberculosis)
THD	total harmonic distortion
TiO2	titanium dioxide (chemical formula)
TLV	threshold limit value
UL	Underwriters Laboratories
U.S.	United States
UV	ultraviolet
UV-A	UV radiation in the range from 315 nm to 400 nm
UV-B	UV radiation in the range from 280 nm to 315 nm
UV-C	UV radiation in the range from 100 nm to 280 nm
UVGI	ultraviolet germicidal irradiation
V	volt
W	watt

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