Related Commercial Resources

CHAPTER 62. ULTRAVIOLET AIR AND SURFACE TREATMENT

ULTRAVIOLET germicidal irradiation (UVGI) uses short-wave ultraviolet (UVC) energy to inactivate viral, bacterial, and fungal organisms so they are unable to replicate and potentially cause disease. UVC energy disrupts the deoxyribonucleic acid (DNA) of a wide range of microorganisms, rendering them harmless (Brickner et al. 2003; CIE 2003). Early work established that the most effective UV wavelength range for inactivation of microorganisms is between 220 and 280 nm, with peak effectiveness near 265 nm. The standard source of UVC in commercial systems is low-pressure mercury vapor lamps, which emit mainly near-optimal 253.7 nm UVC. Use of germicidal ultraviolet (UV) lamps and lamp systems to disinfect room air and air streams dates to about 1900 (Reed 2010). Riley (1988) and Shechmeister (1991) wrote extensive reviews of UVC disinfection. Application of UVC is becoming increasingly frequent as concerns about indoor air quality increase. UVC is now used as an engineering control to interrupt the transmission of pathogenic organisms, such as *Mycobacterium tuberculosis* (TB), influenza viruses, coronavirus, mold, and potential bioterrorism agents (Brickner et al. 2003; CDC 2002, 2005; GSA 2018; McDeVitt et al. 2008; Rudnick et al. 2009; Walker 2007).

UVC lamp devices and systems are placed in air-handling systems, ductwork, and in room settings for the purpose of air and surface disinfection (Figure 1). Control of bioaerosols using UVC can improve indoor air quality (IAQ) and thus enhance occupant health, comfort, and productivity (ASHRAE 2009; Menzies et al. 2003). Detailed descriptions of UVGI components and systems are given in Chapter 17 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*. Upper-air (also commonly called upper-room) devices are installed in occupied spaces to control bioaerosols (e.g., suspended viruses, bacteria, fungi contained in droplet nuclei) in the space. In-duct systems are installed in air-handling units to control bioaerosols in recirculated air and to control microbial growth on cooling coils and other surfaces. Keeping the coils free of biofilm buildup can help reduce pressure drop across the coils and improve heat exchanger efficiency (therefore lowering the energy required to move and condition the air), and eliminates one potential air contamination source that could degrade indoor air quality. UVC is typically combined with conventional air quality control methods, including dilution ventilation and particulate filtration, to optimize cost and energy use (Ko et al. 2001).

This chapter discusses these common approaches to the application of UVC products. It also surveys the most recent UVC design guidelines, standards, and practices and discusses energy use and economic considerations for the application of UVC systems. Photocatalytic oxidations (PCOs), another UV-based HVAC application, are not discussed in this chapter, but are addressed in Chapter 47 of this volume.

1. FUNDAMENTALS

Ultraviolet energy is electromagnetic radiation with a wavelength shorter than that of visible light and longer than x-rays (Figure 2). The International Commission on Illumination (CIE 2003) defines the UV portion of the electromagnetic spectrum as radiation having wavelengths between 100 and 400 nm. The UV spectrum is further divided into UVA (wavelengths of 400 to 315 nm), UVB (315 to 280 nm), UVC (280 to 100 nm), and vacuum UV (VUV; 200 to 100 nm) (IESNA 2000). The optimal wavelength for inactivating microorganisms is 265 nm (Figure 3), and the germicidal effect decreases rapidly if the wavelength is not optimal.

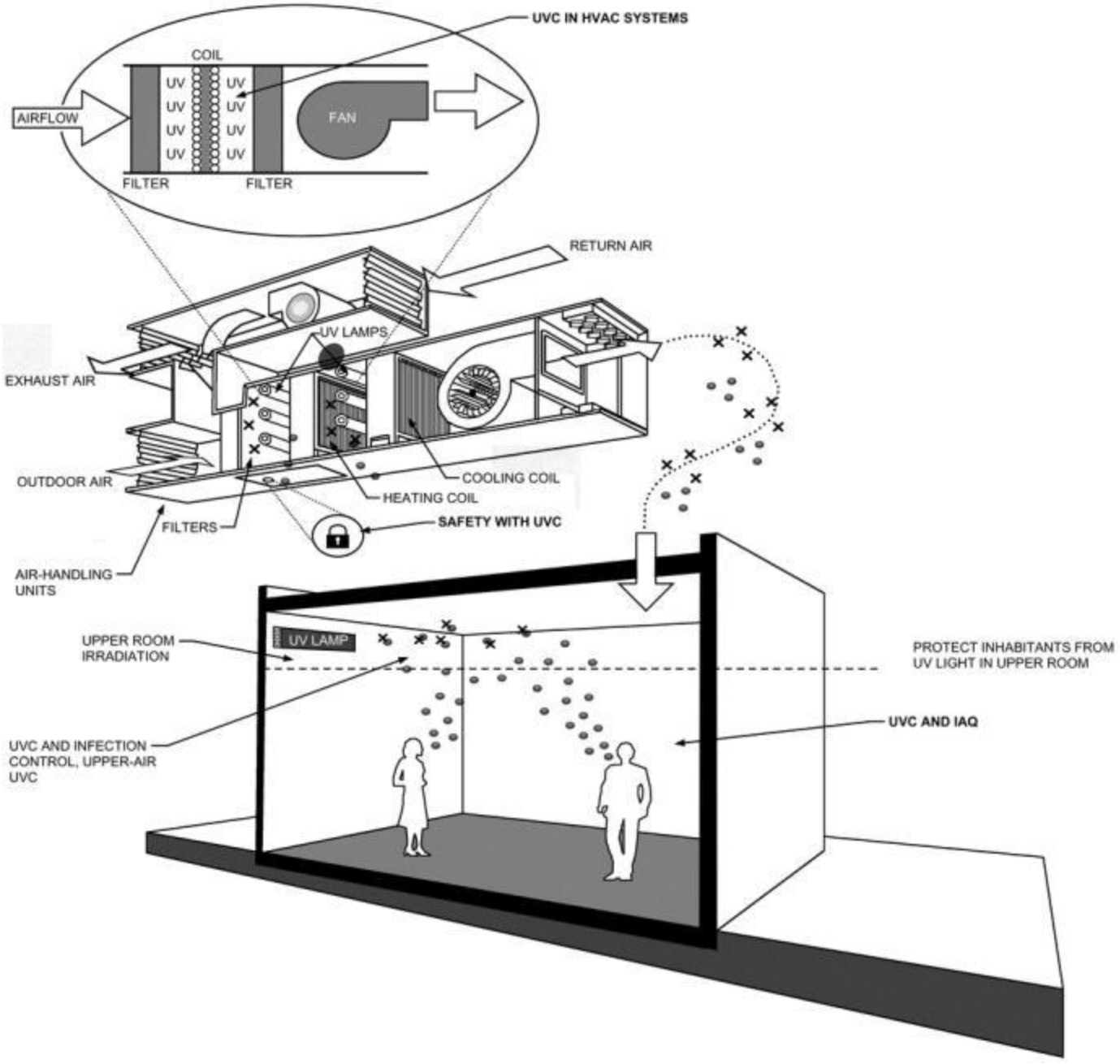

Figure 1. Potential Applications of UVC to Control Microorganisms in Air and on Surfaces (ASHRAE 2022)

UV Dose and Microbial Response

UVGI inactivates microorganisms by damaging the structure of nucleic acids and proteins at the molecular level, making them incapable of reproducing. The most important of these is DNA, which is responsible for cell replication (Harm 1980). The nucleotide bases (pyrimidine derivatives thymine and cytosine, and purine derivatives guanine and adenine) absorb most of the UV energy responsible for cell inactivation (Diffey 1991; Setlow 1966). Absorbed UV photons can damage DNA in a variety of ways, but the most significant damage event is the creation of pyrimidine dimers, where two adjacent thymine or cytosine bases bond with each other, instead of across the double helix as usual (Diffey 1991). In general, the DNA molecule with pyrimidine dimers is unable to function properly, resulting in the organism's inability to replicate or even its death (Diffey 1991; Miller et al. 1999; Setlow 1997; Setlow and Setlow 1962). An organism that cannot reproduce is no longer capable of causing disease (Martin et al. 2008).

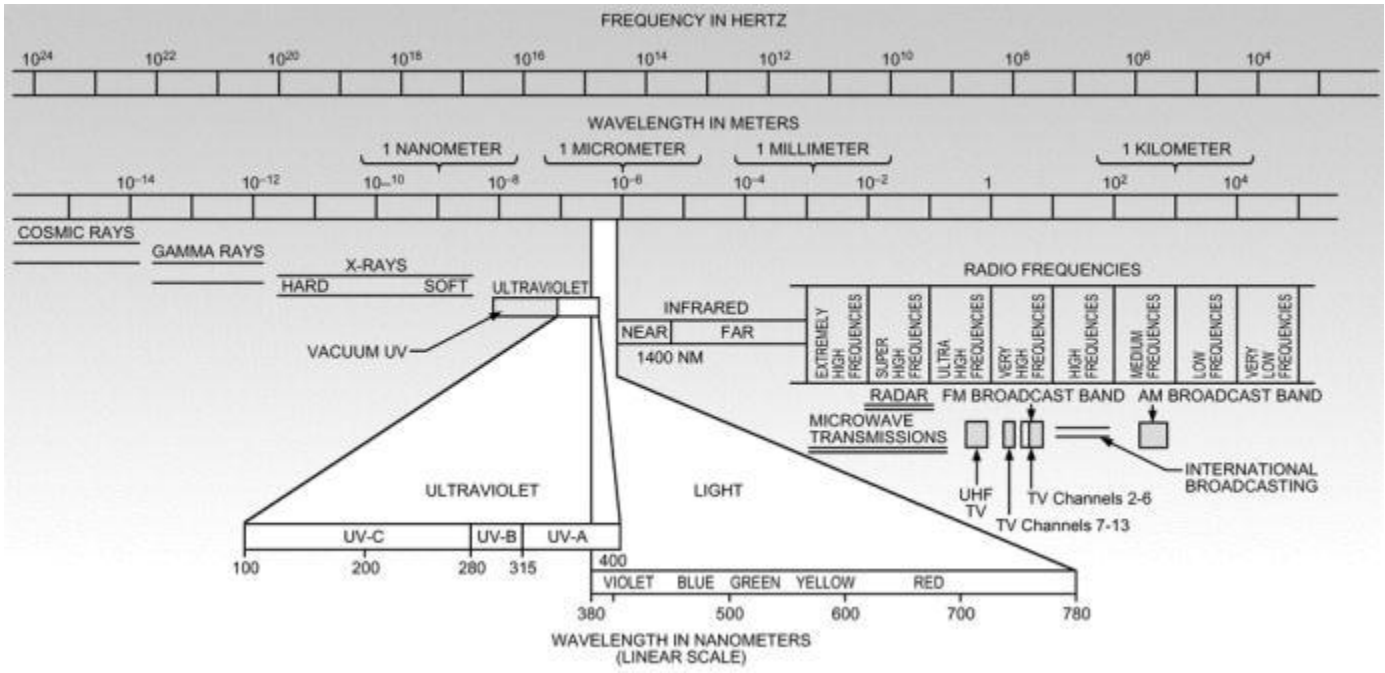

Figure 2. Electromagnetic Spectrum (IESNA 2000)

UVGI effectiveness depends primarily on the UV dose (D_{UV}, μJ/cm^2) delivered to the microorganisms:

$$D_{UV} = It \quad (1)$$

where I is the average irradiance in μW/cm^2, and t is the exposure time in seconds (note that 1 J = 1 W/s). Although Equation (1) appears quite simple, its application can be complex (e.g., when calculating the dose received by a microorganism following a tortuous path through a device with spatial variability in irradiance). The dose is generally interpreted as that occurring on a single pass through the device or system. Although the effect of repeated UV exposure on microorganisms entrained in recirculated air may be cumulative, this effect has not been quantified, and it is conservative to neglect it.

The survival fraction S of a microbial population exposed to UVC energy is an exponential function of dose:

$$S = e^{-kDUV} \quad (2)$$

where k is a species-dependent inactivation rate constant, in cm^2/μJ. The resulting single-pass inactivation rate η is the complement of S:

$$\eta = 1 - S \quad (3)$$

and is a commonly used indicator of overall UVC effectiveness, representing the percentage of the microbial population inactivated after one pass through the irradiance field(s).

Inactivation rate constants (k-values) are species-dependent and relate to the susceptibility of a given microorganism population to UV radiation (Hollaender 1943; Jensen 1964; Sharp 1939, 1940). Measured k-values for many species of viruses, bacteria, and fungi have been published in the scientific literature and previously summarized (Brickner et al. 2003; Kowalski 2009; Philips 2006). As shown in Figure 4, bacteria are generally more susceptible to UVC energy than fungi, but this is not always the case (see Chapter 17 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*). It is more difficult to generalize when it comes to viruses. Reported k-values for different species of microorganisms vary over several orders of magnitude. Consequently, choosing which k-value to use for UVC system design is often difficult and confusing. The variation in reported k-values makes generalizing the use of Equation (2) particularly complicated for heterogeneous microbial populations. Even accurately determining S for one specific microorganism can be difficult, because the reported k-values for the same species sometimes differ significantly.

Variations in published k-values may relate to differences in conditions under which the UV irradiance of the microbial population was conducted (in air, in water, or on surfaces), the methods used to measure the irradiance level, and errors related to the microbiological culture-based measurements of microbial survival (Martin et al. 2008). Because no standard methods are currently available for the determination of inactivation rate constants, care is necessary when applying values reported in the literature to applications under different environmental conditions.

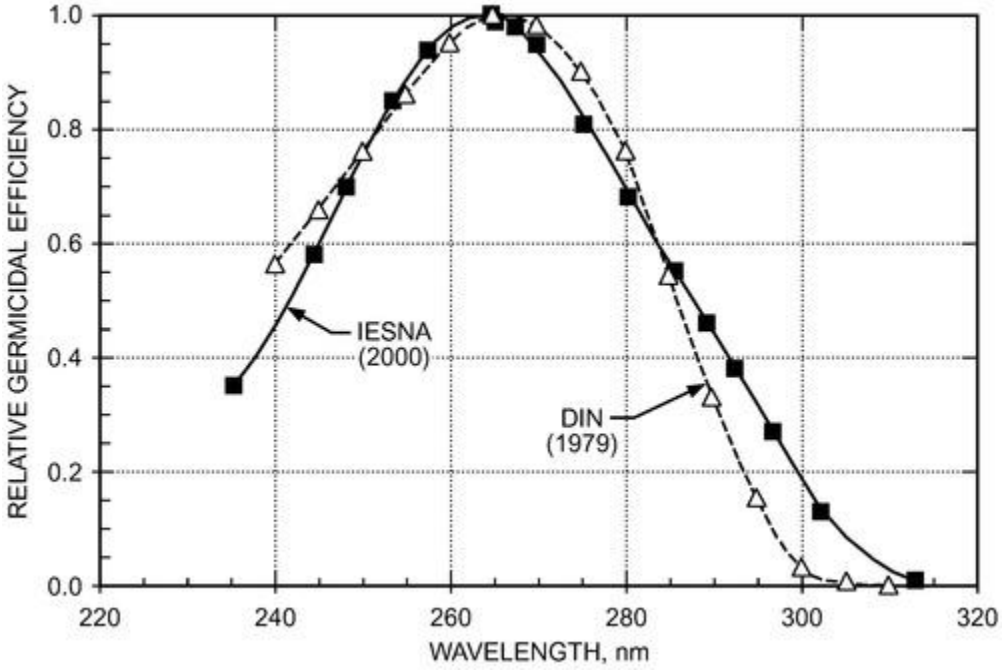

Figure 3. Standardized Germicidal Response Functions

Table 1 Overall Average Rate Constants for Microbial Groups

		Air-Low RH		Air -High RH		Surface		Water	
Microbe	**Type**	***k*, m²/J**	***D*90, J/m²**	***k*, m²/J**	***D*90, J/m²**	***k*, m²/J**	***D*90, J/m²**	***k*, m²/J**	***D*90, J/m²**
Bacteria	Veg	0.38887	6	0.07384	31	0.14045	16	0.08463	27
Viruses	All	0.39985	6	0.2905	8	0.03156	73	0.05798	40
Bacterial Spores	Spores	0.02566	90	0.026	8	0.01823	126	0.01439	160
Fungal cells and yeast	Veg	0.09986	23			0.007	329	0.01008	229
Fungal spores	Spores	0.0073	315			0.00789	292	0.00916	251

Note: Average values in table only provide guidance on relative susceptibility of microorganisms in different media and should not be used for design purposes.

From Equation (3) it can be inferred that a microorganism's susceptibility is inversely proportional to the UV rate constant. The D_{90} dose (i.e., the dose required for 90% inactivation) can be calculated by

$$D_{90} = 2.3026/k \quad \textbf{(4)}$$

This implies that, the lower the rate constant, the higher the inactivation dose required is. Table 1 shows overall relative UV susceptibilities for bacteria, viruses, and fungi in air, water, and on surfaces (Kowalski 2009).

Based on the overall averages, it appears that viruses are over twice as resistant to UVC than bacteria, while fungal spores are greater than three times more resistant than bacteria. In general, doses required for bacteria and viruses are lower in air than on surfaces. The susceptibility of bacteria and viruses is also observed to be lower at high relative humidity levels (above 68%). A summary of over 600 *k*-values for bacteria, viruses and fungi are provided in the literature (Kowalski 2009). Literature also suggests that double-stranded DNA and RNA viruses are more resistant to UVC as compared to single-stranded viruses (Tseng and Li 2007).

While *k* values have been typically determined and applied for water and surface applications, for UVC inactivation in air, the term ***Z*-value** is often used as an alternate to the *k*-value (Kethley 1973). The *Z* value is defined as the ratio of the inactivation rate normalized by UVC irradiance. For all practical purposes, the *Z*-value is equivalent to the *k*-value.

Z-values obtained from experiments for some common aerosolized viruses by different researchers have been summarized as follows (Beggs et al. 2020):

Virus	**UVC Wavelength, nm**	***Z* value, m²/J**
Adenovirus	254	0.0546, 0.0390
Coxscackie B-1	254	0.1108
Influenza A	254	0.1187

Sindbis virus	254	0.1040
Vaccinia virus	254	0.1528, 2.54
MHV coronavirus	254	0.377
Human coronavirus (229E)	222	0.41
Human coronavirus (OC43)	222	0.59

Studies have shown that the SARS-CoV-2 virus is structurally similar to the coronavirus family of viruses in terms of genomic characteristics important for UVC-induced damages, and therefore *Z*-values of 0.377 m^2/J corresponding to the MHV coronavirus has been recommended for UVC inactivation of the SARS-CoV-2 virus.

CDC Guidelines for Upper Air Disinfection (CDC/NIOSH 2009) reference the *Z*-values obtained from UV studies for *M. tuberculosis* and other airborne microorganisms, shown in Figure 4.

UV rate constants of bacteria and viruses have also been estimated by using mathematical models based on base-counting of potential dimers in the virus and found to have good agreement with experimental values (Kowalski 2009).

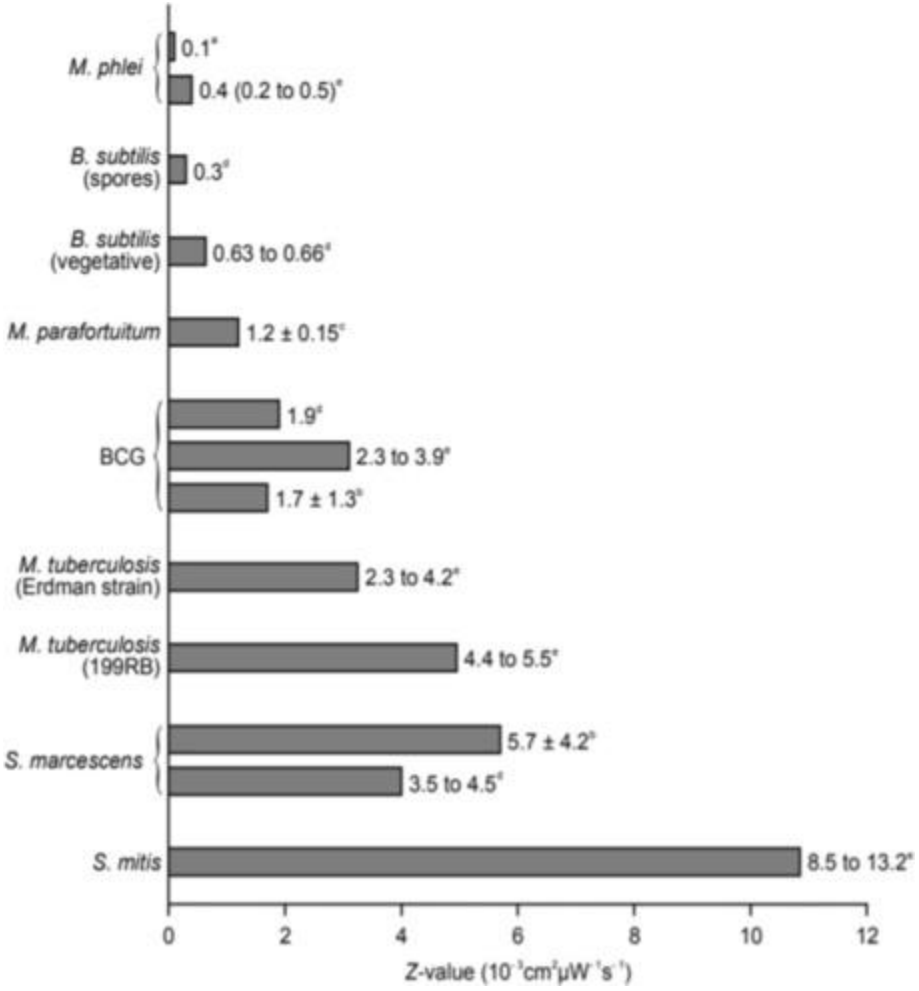

Figure 4. Relative Sensitivity of Selected Airborne Microorganisms to UVGI. The higher the *Z*-value, the greater the susceptibility. Superscripted letters indicate data sources: [a]Kethley 1973; [b]Ko et al. 2000; [c]Miller et al. 2002; [d]Peccia 2000; [e]Riley et al. 1976.

UV Inactivation of Biological Contaminants

The focus of this chapter is application of UVC energy to inactivate microorganisms, specifically bacteria, fungi, and viruses on surfaces and in air streams. The application of UVC for upper-room treatment generally applies to pathogenic bacteria and viruses. Under some circumstances, these pathogens have the potential to be transmitted throughout the HVAC system.

Table 2 Representative Members of Organism Groups

Organism Group	Member of Group
Vegetative Bacteria	*Staphylococcus aureus*
	Streptococcus pyogenes
	Escherichia coli
	Pseudomonas aeruginosa

	Serratia marcescens
Mycobacteria	*Mycobacterium tuberculosis*
	Mycobacterium bovis
	Mycobacterium leprae
Bacterial Spore	*Bacillus anthracis*
	Bacillus cereus
	Bacillus subtilis
Fungal Spores	*Aspergillus versicolor*
	Penicillium chrysogenum
	Stachybotrys chartarum
Viruses	Influenza viruses
	Measles
	SARS
	Smallpox
	Coronavirus

Infectious diseases can be transmitted by a variety of ways. UVC is effective against microorganisms in the air traveling through the UVC irradiation field and may be present on irradiated surfaces.

As shown in Table 2 and Figure 5, viruses and vegetative bacteria are generally most susceptible to UV inactivation, followed by Mycobacteria, bacterial spores, and finally fungal spores. Within each group, an individual species may be significantly more resistant or susceptible, so this ranking should be used only as a general guideline. Note that the spore-forming bacteria and fungi also have vegetative forms, which are markedly more susceptible to inactivation than their spore forms. Viruses are a separate case. As a group, their susceptibility to inactivation is even broader than for bacteria or fungi.

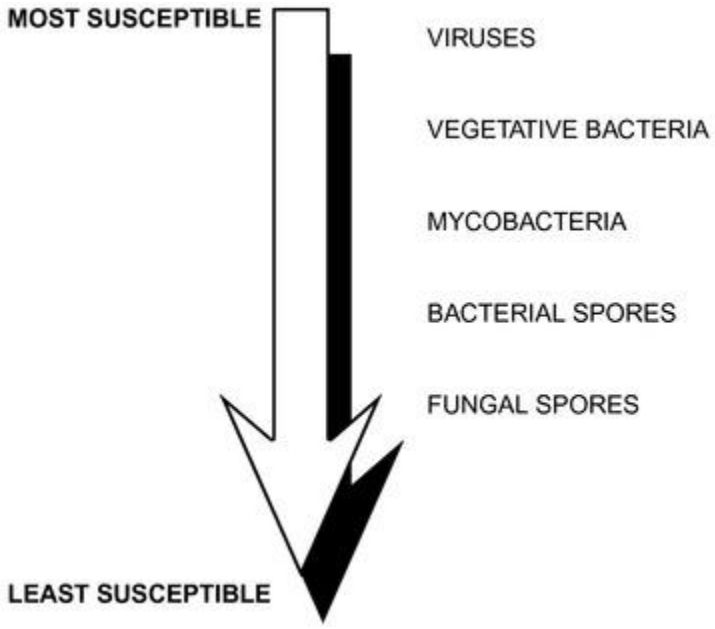

Figure 5. General Ranking of Susceptibility to UVC Inactivation of Microorganisms by Group

2. TERMINOLOGY

A variety of units have been used in UV disinfection for the irradiance and the UV dose. The **irradiance**, sometimes called **intensity**, has the preferred units of W/m^2 in air and surface disinfection. The **UV dose** (or **fluence rate**) has the preferred units of J/m^2 in air and surface disinfection. Conversion factors for the various units that have been used in the literature are provided in Table 3.

Air cleaner. Device or system for removing contaminants from air in a ventilation system, building, or other enclosed space.

Table 3 Conversion Factors for Irradiance and UV Dose

Conversion Factors for Irradiance

(Read down from units to shaded block and then horizontally.)

	W/m^2	
mW/cm^2	$\mu W/mm^2$	$\mu W/cm^2$
	J/m^2-s	
1	10	1000
0.1	1	100
0.001	0.01	1
mJ/cm^2	μW-s/mm^2	$\mu J/cm^2$
	W-s/m^2	
mW-s/cm^2	J/m^2	μW-s/cm^2

Conversion Factors for UV Dose (Exposure Time = 1 second)

(Read up from units to shaded block and then horizontally.)

Air changes per hour (ACH). A measure of the clean air volume added to or removed from a space in 1 h divided by the volume of the space. Sometimes called **air exchange rate**.

Burn-in time. Period of time that UV lamps are powered on before being put into service, typically 100 h.

CADR. clean air delivery rate. One outcome of the AHAM AC-1 test, this is the amount of clean air provided by an air cleaner per time.

Cutaneous damage. Any damage to the skin, particularly that caused by exposure to UVC energy.

Direct irradiation below exposure limits (DIBEL). Germicidally-effective irradiation into an occupied or potentially occupied space with irradiation held below the exposure limit allowed by EN 62471:2008.

Disinfection. Compared to sterilization, a less lethal process of inactivating microorganisms. Less than 6 log reduction.

Droplet nuclei. Residual viable microorganisms in air, following evaporation of surrounding moisture. These microscopic particles are produced when an infected person coughs, sneezes, shouts, or sings. The particles can remain suspended for prolonged periods and can be carried on normal air currents in a room and beyond to adjacent spaces or areas receiving exhaust air.

Dosimeter. An instrument for measuring and monitoring exposure to doses of electromagnetic radiation. These include photochromic paper indicators, which change color upon exposure to accumulated dose values at specific wavelengths.

Equivalent air changes per hour (eACH): The number of ACHs that would be needed in order to provide the equivalent inactivation rate of airborne bacteria or viruses using an upper-room UVC system.

Erythema (actinic). Reddening of the skin, with or without inflammation, caused by the actinic effect of solar radiation or artificial optical radiation. See CIE (2011) for details. (Non-actinic erythema can be caused by various chemical or physical agents.)

Exposure. Being subjected to infectious agents, irradiation, particulates, or chemicals that could have harmful effects.

Far UV. Of, relating to, or being the shortest wavelengths of radiation in the ultraviolet spectrum and especially those between 200 and 230 nm.

Fluence. Radiant flux passing from all directions through a unit area, often expressed as J/m^2, J/cm^2, or $(\mu W \cdot s)/cm^2$.

Germicidal UV (GUV). See Ultraviolet germicidal irradiation (UVGI).

Healthcare-acquired infections (HAIs). Infections acquired by patients during their stay in a healthcare setting.

Irradiance. Power of electromagnetic radiation incident on a surface per unit surface area, typically reported in microwatts per square centimeter ($\mu W/cm^2$). See CIE (2011) for details.

Microorganisms. A microscopic organism, especially a bacterium, fungus, or protozoan.

Permissible exposure time (PET). Calculated time period that humans, with unprotected eyes and skin, can be exposed to a given level of UV irradiance without exceeding the NIOSH recommended exposure limit (REL) or ACGIH Threshold Limit Value® (TLV®) for UV radiation.

Personal protective equipment (PPE). Protective clothing, helmets, goggles, respirators, or other gear designed to protect the wearer from injury from a given hazard, typically used for occupational safety and health purposes.

Photocatalytic oxidation (PCO). A process that involves a light-activated catalyst reacting with organic pollutants to oxidize them.

Photokeratitis. Corneal inflammation after overexposure to ultraviolet radiation (CIE 1993).

Photokeratoconjunctivitis. Inflammation of cornea and conjunctiva after exposure to UV radiation. Exposure to wavelengths shorter than 320 nm is most effective in causing this condition. The peak of the action spectrum is approximately 270 nm. See CIE (1993) for details. Note that different action spectra have been published for

photokeratitis and photoconjuctivitis (CIE 1993); however, the latest studies support the use of a single action spectrum for both ocular effects.

Radiometer. An instrument used to measure radiometric quantities, particularly UV irradiance or fluence.

***Threshold Limit Value*® (TLV®).** An exposure level under which most people can work consistently for 8 h a day, day after day, without adverse effects. Used by the ACGIH to designate degree of exposure to contaminants. TLVs can be expressed as approximate milligrams of particulate per cubic meter of air (mg/m^3). TLVs are listed either for 8 h as a time-weighted average (TWA) or for 15 min as a short-term exposure limit (STEL).

Ultraviolet radiation. Optical radiation with a wavelength shorter than that of visible radiation. (See CIE [1987] for details.) The range between 100 and 400 nm is commonly subdivided into

- UVA: 315 to 400 nm
- UVB: 280 to 315 nm
- UVC: 200 to 280 nm
- Vacuum UV 100 to 200 nm

Ultraviolet germicidal irradiation (UVGI). Ultraviolet radiation that inactivates microorganisms. UVC energy is generated by germicidal lamps that kill or inactivate microorganisms by emitting radiation predominantly at a wavelength of 253.7 nm.

UV dose. Product of UV irradiance and specific exposure time on a given microorganism or surface, typically reported in millijoules per square centimeter (mJ/cm^2).

Wavelength. Distance between repeating units of a wave pattern, commonly designated by the Greek letter lambda λ.

3. UVGI AIR TREATMENT SYSTEMS

Design Guidance

Early guidelines published by General Electric (Buttolph and Haynes 1950), Philips (1985), and Westinghouse (1982) are still used by many system designers today. First et al. (1999), Kowalski (2003, 2006, 2009), NIOSH (2009), and Riley et al. (1976) made meaningful advances in the analysis and modeling of UVGI systems that improved guidance for system design, yet no consensus guidelines exist that comprehensively address all aspects of UVGI system design required to ensure desired performance.

UVC system design today relies on performance data from lamp, ballast, and fixture manufacturers and the experience of system designers. Many equipment manufacturers have methods for estimating the UV dose delivered, which may include using tabulated data charts, mathematical modeling, and complex formulas. Like most HVAC components, UVC systems are often oversized to ensure performance. This oversizing, though conservative, can potentially increase equipment and utility costs, and may result in less energy-efficient systems.

Although application support for UVC technologies is growing and many successful systems have been installed, "the most important needs in the area of UVGI are industry standards to rate devices and installations, as well as guidance for installation and maintenance" (EPA 2017). ASHRAE Technical Committee 2.9, Ultraviolet Air and Surface Treatment, was created in 2003 (initially as a Task Group, converted to a standing Technical Committee in 2007) in part to address these deficiencies by initiating research programs, preparing Handbook chapters, and serving as the cognizant committee for developing the needed standards. So far, two ANSI/ASHRAE standards provide end users with ratings of equipment performance and aid UVC system designers in selecting appropriate components:

- ANSI/ASHRAE *Standard* 185.1-2020, Method of Testing UV-C Lights for Use in Air-Handling Units or Air Ducts to Inactivate Airborne Microorganisms, establishes a test method for evaluating the efficacy of UVC lights for their ability to inactivate airborne microorganisms installed inside general ventilation systems.
- ANSI/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, establishes a similar test method to measure the intensity of ultraviolet lamps on irradiated surfaces under typical HVAC&R operating conditions.

For any application, the ability of UVC to inactivate microorganisms is a function of dose. **Dose** is the length of time of exposure multiplied by the irradiance measured in $\mu W/cm^2$ (see Chapter 17 in the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* for more details). A key difference between surface decontamination and airborne inactivation of organisms is exposure time. In a duct system, exposure time is on the order of seconds or fractions of seconds because of the rapid movement of air through the duct. Therefore, the irradiance must be sufficiently high to provide the dose necessary to inactivate the pathogen in seconds or a fraction of a second, depending upon the configuration and characteristics of the UVC system.

As mentioned previously, organisms differ in their susceptibility to UVC inactivation. Depending on the application, a public health or medical professional, microbiologist, or other individual with knowledge of the threat or organisms of concern should be consulted during the design process.

Upper-Room UVC Luminaires

The primary objective of upper-room (UR) UVC placement and use is to inactivate airborne infectious pathogens. The source of these infectious organisms may be infected humans, animals, or bioaerosols introduced for terrorism purposes. Humans are the predominant sources of airborne agents that infect people (ACGIH 1999). The measles and influenza viruses and the tuberculosis bacterium are three important infectious organisms known to be transmitted indoors by means of air shared, by any means, between infected and susceptible persons. Studies of person-to-person outbreaks indicate at least two transmission patterns: within-room exposure such as in a congregate space, and transmission beyond a room through corridors and by entrainment in ventilation ductwork, through which air is then recirculated throughout the building. ASHRAE also provides guidance on protecting buildings from extraordinary incidents in which a bioterror agent is aerosolized into a building (ASHRAE 2003). Figure 6 shows example components of an UR luminaire.

Upper-room UVC is used as a standalone environmental control or in combination with other interventions, to protect building occupants (Brickner et al. 2003; Kowalski and Bahnfleth 2003). Since the 1930s (Riley and O'Grady 1961; Wells 1955) and continuing to the present day (First et al. 2007a, 2007b; Miller et al. 2002; Xu et al. 2003), numerous experimental studies have demonstrated the efficacy of upper-room UVC. Additionally, evidence of effectiveness has been established for inactivation of tuberculosis (Escombe et al. 2009; Mphaphlele et al. 2015), reducing measles transmission in a school, and the interruption of influenza transmission within a hospital (McLean 1961).

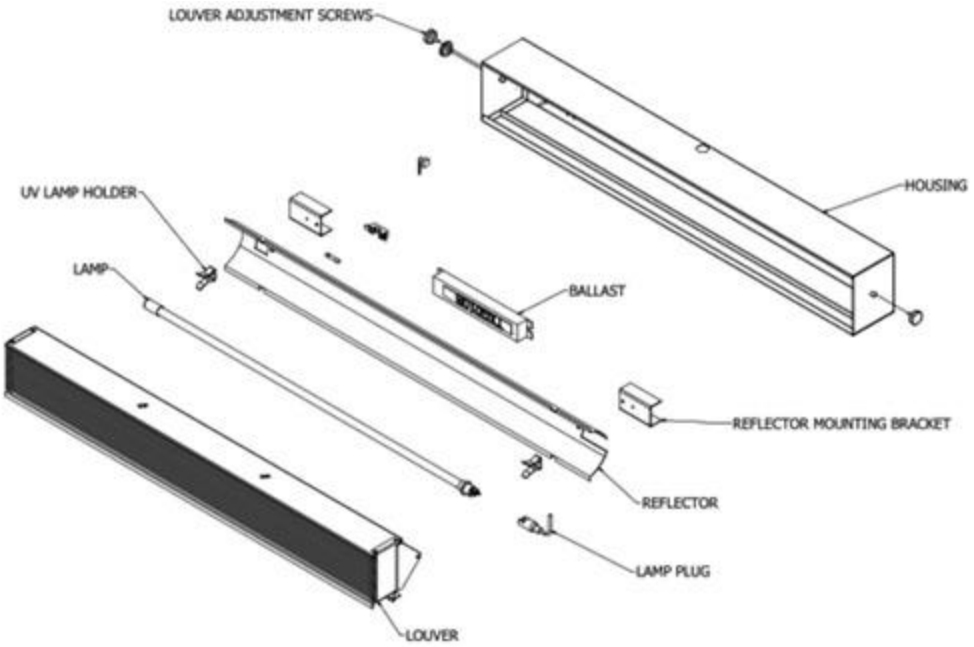

Figure 6. Typical Components of Louvered-Style Upper-Room Luminaire

Upper-room UVC devices are designed to generate a controlled UVC field safely above the heads of room occupants. Settings appropriate to upper-room UVC placement include congregate spaces where undiagnosed and potentially infected persons may share the same space with susceptible persons (e.g., schools, office space, public venues, houses of worship, transportation hubs, health care facilities, homeless shelter). Parameters for UVC effectiveness include room configuration, UV fixture placement, and the adequacy of air mixing in, bringing contaminated air into the upper UV zone. Common corridors potentially used by unknown infected persons would also benefit from upper-room UVC luminaires (see Figures 7 and 8 for illustrations of upper-room pathogen control using UVC). Upper-room UVC is very effective in areas with no or minimal ventilation, able to provide 10 or more eACH (Miller et al. 2002; Mphaphlele et al. 2015). For upper-room UVC to be effective, room airflow patterns (natural and mechanical) should ideally provide good air mixing. Infectious microorganisms enter the UVC zone and are inactivated, thus reducing the risk of exposure of occupants to airborne infectious agents. Studies using natural and/or mechanical ventilation and UVC luminaires have shown it to be an effective, low-cost intervention for use in airborne infection control (Escombe et al. 2009; Mphaphlele et al. 2015).

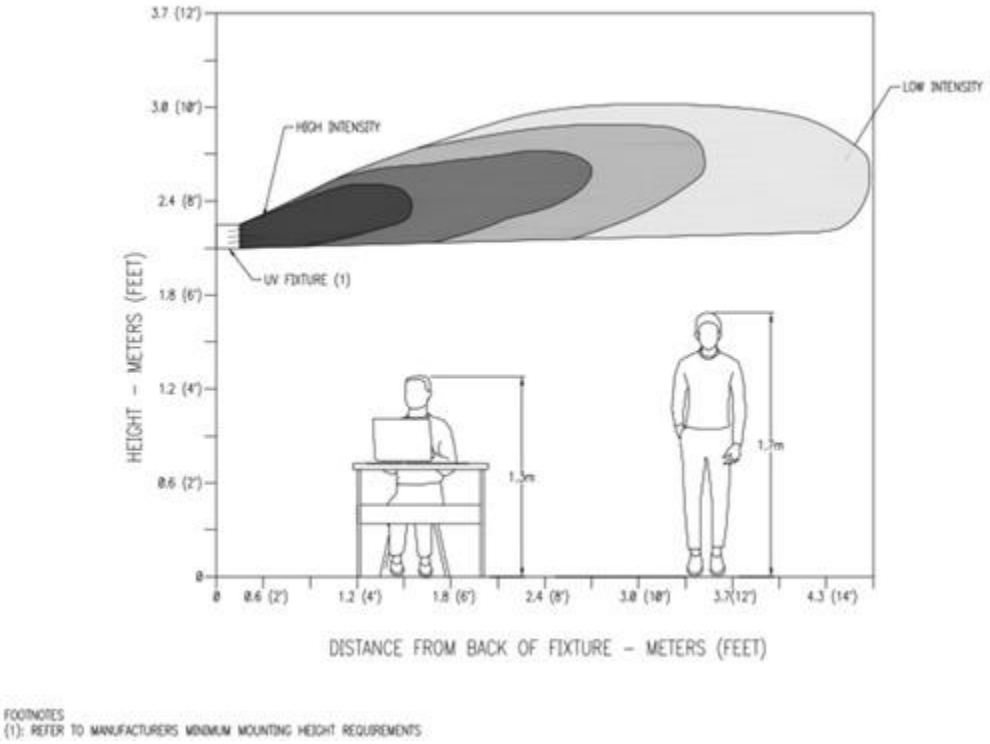

Figure 7. Typical Elevation View of Louvered Luminaire Showing UVGI Energy Safely above Heads of Room Occupants

Upper-room UVC devices are designed and installed to irradiate only air in the upper part of the room, as shown in Figures 7 and 8. UVC devices should be appropriately spaced to accommodate the conditions of the space, including area, shape, height, architectural features, obstructions, and other environmental conditions of the space in which air is to be disinfected. Figures 9 and 10 show examples of upper-room fixture placement. An upper-room computer-aided design (CAD) tool (Figure 11) can calculate the average fluence in the upper room with some basic inputs of room geometry, reflectivity, and device specifications (Rudnick et al. 2012; Vincent et al. 2013; Zhang et al. 2012). Additionally, computational fluid dynamics (CFD) can be used to understand the interaction between airflow and upper-room UVC (Gilkeson and Noakes 2013; Xu et al. 2013; Zhu et al. 2013).

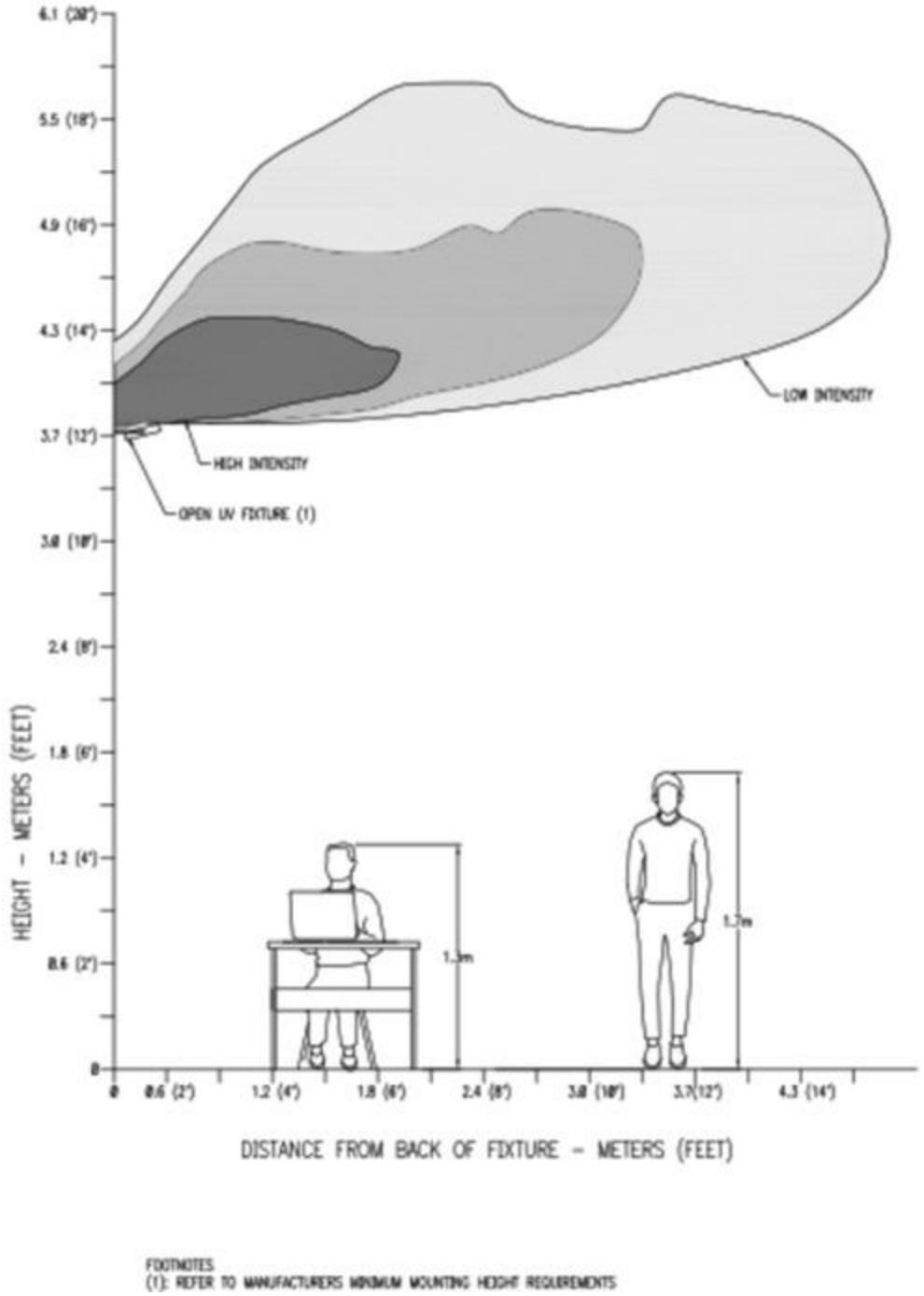

Figure 8. Typical Elevation View of Open-Fixture Luminaire Used for Tall Spaces

Figure 9. Upper-Room UVC (Circled) Treating Congregate Setting (TUSS Project, St. Vincent's Hospital, New York City)

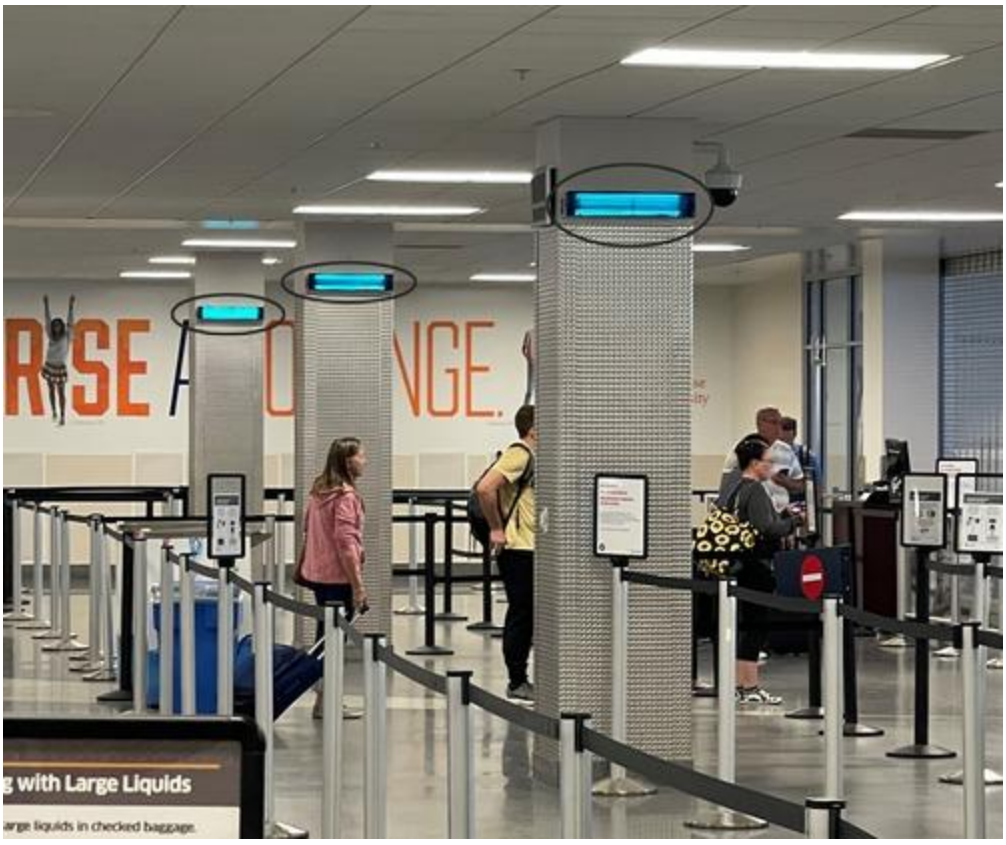

Figure 10. Upper-Room UVC Luminaires (Circled) in Airport

Upper-room UV devices can use a variety of UV sources and can accommodate various voltages. Fixtures are available in open or restricted energy distribution (louvered), depending on the space to be treated. UVC fixtures are selected based on the space requirements, as stated above. Applications with higher ceilings may allow for open fixtures instead of louvered fixtures, which may allow for a larger active upper-room disinfection zone. For occupied spaces with lower ceilings, various louvered upper-room UVC devices (wall-mount, pendant, corner-mount, and ceiling) are available for use in combination and should be mounted at least 2.3 m from the floor to the bottom of the fixture. The fixture should be mounted so that its UV energy is distributed parallel to the plane of the ceiling. Some louvered

fixtures are designed to have an adjustable or upward energy distribution, and care should be taken to limit reflection from the ceiling. Device construction and placement should be considered to prevent excessive ultraviolet energy from striking occupants below. For example, in high-risk areas such as corridors of infectious disease wards, a maximum UV irradiation of 0.4 μW/cm^2 at eye level is an acceptable engineering guide (Coker et al. 2001). No long-term health effects of UVC exposure at these levels in the lower occupied part of rooms are known. Figure 7 shows a typical elevation and corresponding UV levels for ceilings below 3.7 m, and Figure 8 illustrates typical UVC energy distribution for open-room luminaires used in tall spaces above 3.7 m.

Table 4 Suggested UVC Fixture Mounting Heights

	Wall-Mounted Fixtures*		Ceiling-Mounted Fixtures*	
	Wall Mount	**Corner Mount**	**Pendant**	**Pendant with Fan**
Beam pattern	180°	90°	360°	360°
Minimum ceiling height	2.44 m	2.44 m	2.89 m	2.89 m
Fixture mounted height	2.1 m	2.14 m	2.44 m	2.44 m
Ideal UVC intensity for effective disinfection	> 10 μW/cm^2	> 10 μW/cm^2	> 10 μW/cm^2	> 10 μW/cm^2

Source: Based on Coker et al. (2001)

* Appropriately designed UV fixtures are available for all locations. Only the most commonly used have been included in the table.

Application guidance with placement criteria for UV equipment is provided by Boyce (2003), CDC (2005), CIE (2003), Coker et al. (2001), First et al. (1999), IESNA (2000), and NIOSH (2009). An example of the guidance provided by Coker et al. is shown in Table 4. Additionally, manufacturer-specific advice on product operation and placement should be followed, specifically manufacturer's recommended mounting height. A new computer-aided lighting software program has been modified to help automate the placement of fixtures, and to calculate the uniformity and average UV provided (Brickner et al. 2009). Upper-room UVC fixtures that are typically used in developed countries are often cost-prohibitive for use in less developed parts of the world. International guidance is needed to understand best practice for UVC application in the developing world where extensive drug-resistant TB is an increasing global threat (Nardell et al. 2013).

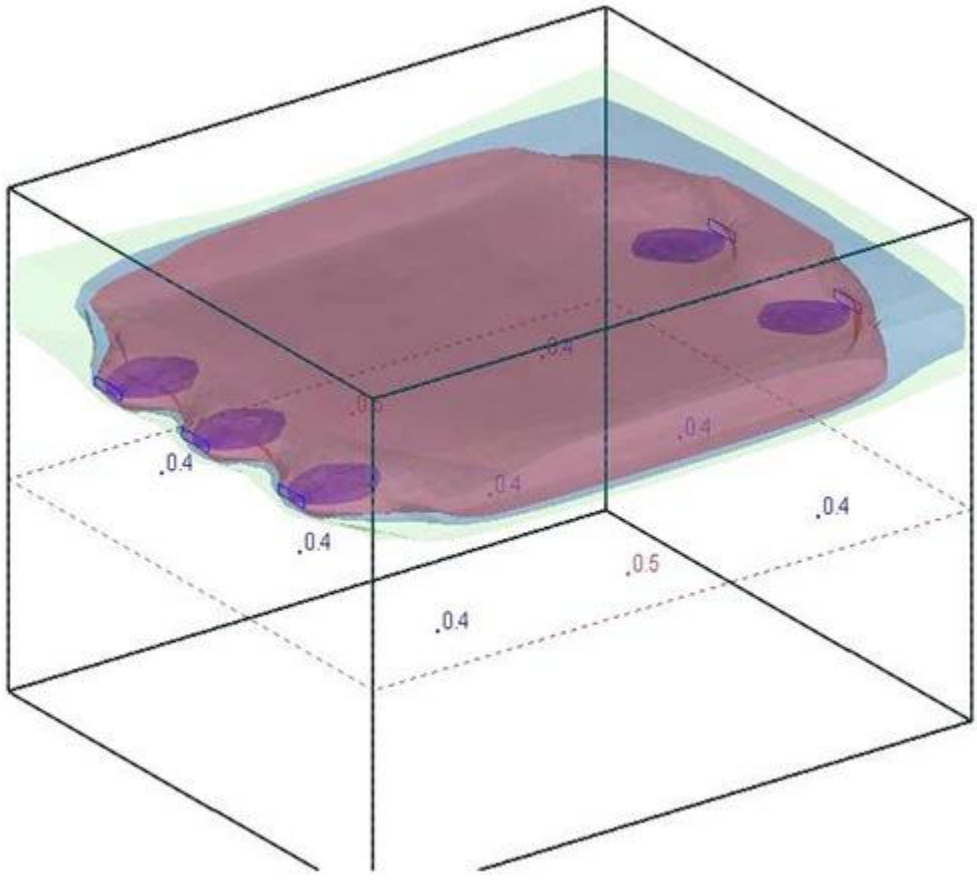

Figure 11. CAD-Based Tool Showing UVC Fluence and Eye-Level Irradiance

Some upper-room installations rely on air convection and mixing to move air from the lower to the upper portion of the room, where it can be irradiated and airborne microorganisms inactivated (Kethley and Branc 1972). The overall

effectiveness of upper-room UVC systems improves significantly when the air in the space can be well mixed. Although convection air currents created by occupants and equipment can provide adequate air circulation in some settings, mechanical ventilation systems that maximize air mixing are preferable. If mechanical ventilation is not possible, fans can be placed in the room to enhance mixing. Many fixtures incorporate a safety switch that breaks the circuit when fixtures are opened for servicing and should contain baffles or louvers appropriately positioned to direct UV irradiation to the upper air space. Baffles and louvers must never be bent or deformed.

A UVC installation that produces a maintained, uniform distribution of UV irradiance averaging between 30 and 50 $\mu W/cm^2$ is effective in inactivating most airborne droplet nuclei containing mycobacteria, and is presumably effective against viruses as well (First et al. 2007a, 2007b; Miller et al. 2002; Xu et al. 2003). Beyond UVC irradiance, effectiveness of upper-room UVC is related to air mixing, relative humidity, and the inherent characteristics of the pathogenic organisms being addressed (Ka et al. 2004; Ko et al. 2000; Rudnick 2007). Effectiveness can improve greatly with well-mixed air (First et al. 2007a, 2007b; Miller et al. 2002; Riley and Permutt 1971; Riley et al. 1971), so ventilation systems that maximize air mixing receive the greatest benefit from upper-room UVC. Relative humidity should be less than 60%; levels over 80% rh may reduce effectiveness (Kujundzic et al. 2007; Xu et al. 2003).

Depending on the disinfection goals, upper-room devices should be operated similarly to in-duct UVC systems. Systems designed to reduce or eliminate the spread of airborne infectious diseases in buildings with continuous occupancy and/or with immunocompromised populations should be operated 24 h per day, 7 days per week. Upper-room systems designed for improved indoor air quality installed in more traditional commercial buildings may be operated intermittently, or powered on during hours of normal building occupancy and powered off when the facility is empty. This may provide acceptable indoor air quality during periods of building occupancy, simultaneously saving energy, and requiring less frequent lamp replacements. However, intermittent operation must be factored into the initial system design because cycling UV lamps on and off may negatively affect lamp and ballast performance and life of equipment.

Direct Irradiation Below Exposure Limits (DIBEL)

Using ultraviolet (UV) radiation emitted directly into occupied spaces and exposing occupants to a dose below the accepted actinic exposure limit (EL) is referred to as **direct irradiation below exposure limits (DIBEL)** (Allen 2021). DIBEL depends on low doses of UVC over longer periods of time. Focusing on UVC DIBEL in the 240 to 280 nm range, the primary inactivation mechanism is due to damaging absorption of the UVC photon by proteins, RNA, and DNA. Germicidal activity is typically maximum at about 260 to 265 nm but depends on the specific pathogen. Since the peak efficacy occurs near to the extremely strong resonance emission line of low-pressure mercury lamps at 254 nm, there is an extensive decades-old library of inactivation data on hundreds of pathogens at 254 nm (Kowalski 2009).

In-Duct UVC Systems: Airstream Disinfection

Airstream disinfection systems where UV lamps are installed in HVAC ductwork or in air handling units are the most efficient and most effective means of controlling indoor air quality and reducing airborne levels of pathogens. Airborne microorganisms are up to 10 times more susceptible to UV exposure in air than in water, and this makes for thorough and rapid disinfection. UV was first successfully used for air disinfection in 1936 when UV lamps were installed in ventilation supply air in a surgical operating room (Hart 1937). The first UV ventilation air disinfection system to be installed in schools significantly reduced the incidence of measles (Riley 1972). UV air disinfection systems were installed across entire communities in the late 1940s and demonstrated reductions in community transmission rates of measles and chickenpox (Wells 1950). The effectiveness of UV against airborne tuberculosis has been well demonstrated (Riley 1961). The installation of UV air disinfection in an office building resulted in a reduction of respiratory symptoms (Menzies 2003).

The principal design objective for an in-duct UVC air disinfection system is to distribute UV energy in a section of the duct or air-handling unit (AHU), to deliver the appropriate UV dose to air moving through the irradiated zone with minimum system power. Using materials such as aluminum or other highly reflective materials inside the duct or air handler can improve UVC system performance by reflecting UVC energy back into the irradiated zone. Using materials such as aluminum or other highly reflective materials can increase reflectivity. Properly designed in-duct UV air disinfection systems are also able to maintain the cleanliness of cooling coil surfaces and condensate pans, when the UV lamps are installed downstream of the cooling coil. Systems specifically designed for coil and condensate pan applications may have limited or reduced air disinfection capabilities.

Design dose is a function of the design-basis microbe (see Tables 1 and 2) and the desired level of disinfection. Generally, single-pass inactivation efficiencies are specified, analogous to the MERV specification of a particulate filter. In some cases, the design disinfection level may be a true performance specification based on the exposure in an occupied space. Determining this single-pass performance requires analysis of the entire system that is used. Which approach is selected depends on the type of application. Laboratory/hospital installations are more likely to have specific, identified microbial targets than, for example, school or office building installations. The required average irradiance for a typical in-duct system is on the order of 1000 to 10,000 $\mu W/cm^2$, but it could be higher or lower depending on the application requirements.

In-duct air disinfection systems should be designed to have the desired single-pass inactivation level under worst-case conditions of air temperature and velocity in the irradiated zone. The worst-case performance reflects the combined effect of the number/power of UVC fixtures; air residence time, which is inversely proportional to air velocity; and lamp/ballast characteristics, including wind chill effect and lamp depreciation (as discussed in Chapter 17 of the

2020 *ASHRAE Handbook—HVAC Systems and Equipment*). Lau et al. (2009) showed that it may be advantageous to use simulation to determine the design condition, given the complex interactions between air temperature, velocity, and lamp performance. Lamps may be located anywhere in an air conveyance system; however, some locations provide more efficiency and potentially greater benefit. In most cases, the lowest maximum velocity in a system occurs inside an air-handling unit. For this reason, and because it provides the ability to treat air from many spaces and simultaneously irradiate cooling coils and condensate pans, this is a very common choice, although systems may also be located in air distribution ducts.

Because they are typically installed in air handling units, most in-duct systems are designed for an air velocity of around 2.5 m/s. At this velocity, an irradiance zone of 0.6 m in length achieves 0.25 s of UV exposure. As a rule of thumb, in-duct systems should be installed in a location that can provide a minimum of 0.25 s of UV exposure; otherwise, system cost and power consumption can increase. UVC devices are most often located downstream of the heating/cooling coils. However, in some cases, mounting UV fixtures upstream of the coil may result in warmer in-duct air temperatures, providing increased lamp performance. The trade-off is reducing the effectiveness of disinfection of the cooling coil and forgoing irradiation of the drain pan that lamps mounted downstream of the coil provide.

In-duct air disinfection systems designed to reduce the spread of airborne infectious diseases (e.g., tuberculosis, influenza) in buildings with continuous occupancy and/or with immunocompromised populations (e.g., hospitals, prisons, homeless shelters) should be operated on a continuous basis. However, properly designed systems installed in more traditional commercial buildings (e.g., offices, retail, schools) can be operated intermittently, or powered on during hours of normal building occupancy and powered off when the facility is empty. This may save energy costs and require less frequent lamp replacement while providing acceptable indoor air quality during periods of occupancy. However, the effect of intermittent operation on lamp and ballast life must be factored into the design analysis: cycling reduces the operating hours to failure of hot cathode lamps. In-duct UVC should always be used in combination with proper filtration. Filters may help to protect UV lamps from dust and debris accumulation which may reduce UV output over time, and filters enhance the overall air cleaning capabilities of the system.

Combining UV lamps and filters provides optimum removal rates of all pathogens. Filters will remove larger pathogens, including spores, which tend to resist UV exposure. Smaller pathogens that may penetrate the filters tend to be susceptible to UV exposure. Filters are rated according to the minimum efficiency reporting value (MERV) specified by ASHRAE (2017). ASHRAE has recommended that HVAC filters should be upgraded to at least a MERV 13 rating where possible to reduce the airborne transmission of disease (ASHRAE 2021a). Typical commercial ventilation systems operate with air velocities of about 2.5 m/s, and not all systems can handle a MERV 13 filter without experiencing increased pressure losses and reduced airflow. However, a viable alternative is to combine a UV system with a MERV 8 filter, which provides approximately the same performance as a MERV 13 filter depending on total UV power output (Kowalski 2021). The low dynamic pressure losses of the MERV 8 filter and the UV lamps ensure that any effects on total system airflow will be minimal.

Adding UV lamps to an existing ventilation system will increase the removal rates of airborne pathogens. The percentage removal rates depend on the total UV lamp power and the air velocity, which define the exposure time. The pathogen removal rates can be assessed based on the UV dose imparted to the air stream. For any given pathogen whose UV susceptibility is defined by a UV rate constant k, the single-pass removal rate RR can be computed from the exposure dose, which depends on the average irradiance I and the exposure time t as follows:

$$RR = 1 - e^{-kIt} \quad (5)$$

The removal rate RR for any particular pathogen is usually the main design criteria used for specifying system performance. Exposure time is critical to inactivation of pathogens, and it is recommended that systems be designed with a minimum exposure time of 0.25 s (Kowalski 2009). The increased performance due to the addition of UV lamps can be assessed in terms of the effectiveness, given in Equation (4). In this case, C_{UV} is the steady-state airborne concentration with UV lamps installed and C_0 is the baseline steady-state condition with air cleaning, and the equation is rewritten as follows:

$$\varepsilon = 1 - (C_{uv}/C_0) \quad (6)$$

It can be convenient to express the added performance of an air cleaner in terms of the effective increase in air change rate, or the equivalent air change rate (eACH). In the case of a UV system added to an existing ventilation system, the increase in performance due to UV is given by the equivalent air change rate (eACH) as follows:

$$\text{eACH} = \left(\frac{C_0}{C_{uv}} - 1\right) \text{ACH} \quad (7)$$

In cases where both a filter and UV lamps are added to a ventilation system, as shown in Figure 12, the removal rates of the two components can be combined mathematically. The total removal rate of a pathogen population RR_{TOT} is computed from the removal rate through filter RR_f and the removal rate through the UV lamps RR_{uv} as follows:

$$RR_{TOT} = 1 - (1 - RR_f)(1 - RR_{uv}) \quad (8)$$

The removal rate through the filters is determined based on the pathogen diameter and the specific filter performance curve (Kowalski 1999). The removal rate through the UV component can be computed analytically

(Kowalski 2009).

$$\text{CADR} = \text{RR} \times Q \quad \textbf{(9)}$$

The first accurate sizing guidelines were presented by Luckiesh (1942) and similar guidelines were presented by Phillips (1985). Approximate parameters for sizing UV systems in terms of UV power, airflow, and duct size can be adapted from systems whose performance has been verified. Several UV systems with different lamp arrangements and UV power levels were tested in airflow against three different microbes under a controlled study designed to measure their performance (EPA 2006). System performance in these tests was largely a function of UV lamp power P alone (Kowalski 2009). The performance of any successful system can be duplicated by scaling the systems up or down in size per the following dimensionless constant F (Kowalski 2009):

$$F = \rho \frac{kPL}{Q} \quad \textbf{(10)}$$

where

P = UV power output, m^2/J
Q = airflow, m^3/s
L = duct length, m
ρ = reflectivity
k = UV rate constant, m^2/J

If the value of F is established for any successful air disinfection system, then the same dose would be achieved by UV systems of different airflows, UV power levels, reflectivity, and duct lengths that produce the same value of F computed from Equation (10). The chosen value of k is arbitrary as it merely serves as a dimensionless conversion factor.

An alternative to sizing UV air disinfection systems based on a specific pathogen is to size the system based on UV dose alone. Typical UV air disinfection systems produce UV doses in the range of 15 to 100 J/m^2 (1.5 to 10 mJ/cm^2) or higher (Kowalski 2009). A typical UV dose for a highly effective UV system would be around 15 J/m^2 (1.5 mJ/cm^2), and this would be a reasonable sizing parameter for commercial buildings and schools.

Regardless of the dose used to size a UV system, the ambient conditions need to be accounted for. The air temperature and air velocity produce a cooling effect (windchill) on lamps that reduces their UV output. UV systems should be sized to account for cooling effects in the design phase, and this typically means increasing total UV power above that based on the air temperature and relative humidity (Lau 2009).

Standards for testing UV air disinfection system performance has been developed under ANSI/ASHRAE *Standard* 185.1-2020. Such tests involve aerosolizing surrogate pathogens and measuring the reduction of airborne concentrations on a single pass at standard AHU velocities of 2.5 m/s. An alternative to bioassay testing is to perform a photometric test to verify the irradiance levels produced by the in-duct system.

Studies of Airstream Disinfection Effectiveness

Laboratory studies (e.g., RTI 2005; VanOsdell and Foarde 2002) conclusively demonstrate the ability of commercially available UVC equipment to achieve a high level of disinfection of moving airstreams. These studies have generally involved tests with surrogates rather than actual infectious disease agents, but it can be assumed that an infectious agent with a k-value similar to an experimental surrogate will be similarly inactivated. Previous field studies showed clinical effectiveness (i.e., reduced incidence of infection) (Nagy et al. 1954; Rentschler and Nagy 1940), but similar recent studies are lacking. Although pilot studies have begun (Bierman and Brons 2007; Rudnick et al. 2009), further recorded field studies are needed to benchmark installed system performance. Many UV airstream disinfection systems have been installed in hospital environments to help reduce pathogens by complementing conventional dilution/filtration systems.

In-Room Air Cleaners

In-room air cleaners (or air purifiers) may be portable, standalone, or installed in a room separate from the HVAC system. In-room also includes devices such as installed wall units or ceiling-mounted devices.

In-room air cleaners may incorporate several different technologies. UV is often included with in-room air cleaners with filtration. It may be used by itself or with other technologies.

Room air cleaners are usually rated using the AHAM AC-1 test by the **clean air delivery rate (CADR)**, which is the amount of clean air the device delivers based on one of three types or particles representing different size fractions of likely airborne dust. For devices that only remove particles from the air, the CADR is a good surrogate for most bioaerosol removal; however, since UV inactivates microorganisms and viruses rather than removing them from the air, the AC-1 CADR may be lower than the actual level or removal and inactivation for these devices.

In March 2022, AHAM released a new test method specifically for removal and inactivation of microorganisms and viruses. This test, AC-5 (AHAM 2022), gives an m-CADR, which can be used like a CADR for the clean air estimates when defining clean air as air without, for example, active disease-causing organisms. Thus, the m-CADR should be used in the calculations for devices that incorporate UV. This test is extremely new, so results are likely to be difficult to find.

In-room air cleaners may be used to augment HVAC air cleaning, to clean air near contaminant sources, or in lieu of HVAC where there is enough fresh air from other sources to meet the ASHRAE minimum levels.

To determine whether the level of clean air meets the needs of a specific space, one may use one of the on-line calculators such as the Equivalent Outdoor Air Calculator (ASHRAE 2021b; tinyurl .com/equivOAcalc) or do the simple math oneself. To meet the goal of clean air, the first step is to determine or chose a number of air changes per hour. There is guidance in various ASHRAE standards for some types of spaces but not for all. If the space of interest does not have a standard level, a clean air change rate (eACH) can be used. To determine the contribution of the in-room air cleaner, use the room volume of a space and the CADR of the in-room device to determine the eACH for the device:

$$\text{eACH} = m\text{-CADR}/(60\ \text{min/h}) \quad \textbf{(11)}$$

The contribution from outdoor air to the same space would be calculated similarly. For clean outdoor air, use all of the values in volume of airflow converted to eACH. Recently, this has been the basic assumption when examining spaces for COVID reduction, because viruses from human sources should not be in outdoor air. However, this assumption will not hold for all contaminants. For contaminated outdoor air, multiple the airflow rate of outdoor air by the efficiency of any air cleaner the outdoor air comes through to determine the eACH. Do the same for the recirculated air in the HVAC. Once this is done, add the values together to determine if the total of the eACH is sufficient. If not, add another in-room air cleaner, more outdoor air, or a better HVAC air cleaner.

4. HVAC SYSTEM SURFACE TREATMENT

Coil and Drain Pan Irradiation

Conditions in HVAC systems can promote the growth of bacteria and mold-containing biofilms on damp or wet surfaces such as cooling coils (Figure 12), drain pans (Levetin et al. 2001), plenum walls, humidifiers, fans, energy recovery wheels, and filters. Locations in and downstream of the cooling coil section are particularly susceptible because of condensation and carryover of moisture from coil fins. Cooling coil fouling by biofilms may increase coil pressure drop and reduce airflow and heat exchange efficiency (Montgomery and Baker 2006). Filters capture bacteria, mold, and dust, which may lead to microbial growth in damp filter media. As the growth proliferates, a filter's resistance to airflow can increase. This can result in more frequent filter changeouts and increased exposure to microbes for maintenance workers and building occupants. As airflow and coil performance degrades, so does the air quality in occupied spaces (Kowalski 2006).

Conventional methods for maintaining air-handling system components include chemical and mechanical cleaning, which can be costly, difficult to perform, and dangerous to maintenance staff and building occupants. Vapors from cleaning agents can contribute to poor air quality, chemical runoff contributes to groundwater contamination, and mechanical cleaning can reduce component life. Furthermore, system performance can begin to degrade again shortly after cleaning, as microbial growth reappears or reactivates.

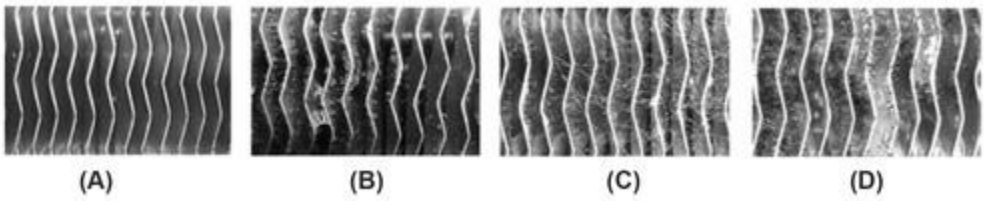

Figure 12. Clean and Biofouled Heat Exchangers and 28 Days of Growth: (A) Clean, (B) 10% Fouled, (C) 30% Fouled, and (D) 40% Fouled (Pu et al. 2010)

UVC can be applied to HVAC systems, typically in air-handling units, to complement conventional system maintenance procedures (Bahnfleth 2011) and has been shown to be effective in reducing air-side pressure drop and increasing air-side heat transfer coefficient of wetted cooling coils (Bahnfleth 2017). A large dose can be delivered to a stationary surface with a low UVC irradiance because of the essentially infinite exposure time, making it relatively easy to cost-effectively prevent the growth of bacteria and mold on system components. In contrast to air disinfection irradiance levels, which may exceed 1000 μW/cm^2, coil surface irradiance levels on the order of 1 μW/cm^2 can be effective (Kowalski 2009), although 50 to 100 μW/cm^2 is more typical. Using reflectors to focus lamp output on surfaces may reduce the power required for surface treatment, but at the expense of reducing air treatment effectiveness. Potential advantages of UVC surface treatment include keeping surfaces clean continuously rather than periodically restoring fouled surfaces, no use of chemicals, lower maintenance cost, and potentially better HVAC system performance.

Lamps can be installed to target problematic components such as cooling coils, condensate pans, or filters (Figure 13), or applied to give broad distribution of UVC energy over an entire enclosure (e.g., mixing box/plenum) that might have microbial activity. Like in-duct air-treatment equipment, systems for surface treatment in air-handling units should be designed to withstand moisture and condensate and selected to operate over a full range of system operating conditions.

Alternative and Complementary Systems

ASHRAE (2020) identifies the following demonstrated ways of reducing airborne infectious disease transmission:

- UVGI (UVC)
- Central system filtration
- Dilution, personalized, general, and local exhaust ventilation
- Control of indoor temperature and relative humidity
- Zone pressurization
- Optimizing airflow patterns and directional airflow
- In-room air-cleaning systems

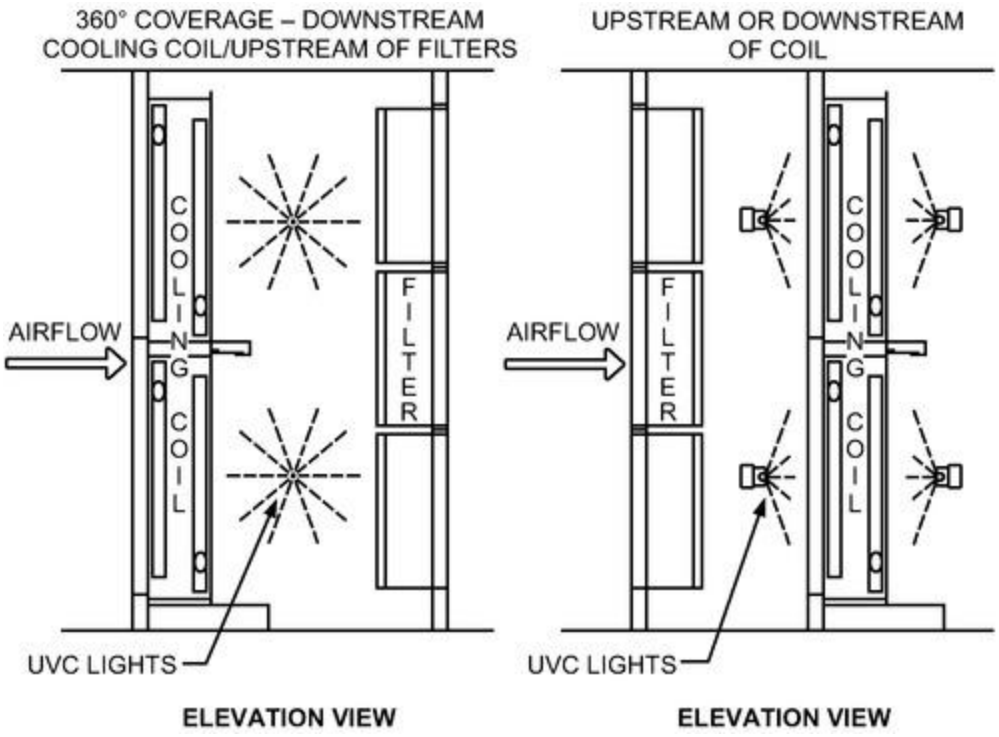

Figure 13. Section View of Typical HVAC Surface Treatment Installations

From one perspective, these may be viewed as distinct, mutually exclusive alternatives for bioaerosol control. In principle, ventilation alone, filtration alone, or UVC alone can yield the same level of control of a given contaminant source. However, in most cases, multiple modes of air quality control are used in the same system, often as a result of code requirements. For example, air quality codes for commercial buildings based on ASHRAE *Standard* 62.1 minimally require both dilution ventilation and particulate filtration at prescribed levels.

When used in combination with other mandatory air treatment modes, UVC provides an incremental benefit. For example, if a particulate filter removes 85% of a given agent in an incoming airstream and a UVC system with a single-pass efficiency of 85% for the same contaminant is installed in series with it, the combined filter/UVC system would have a combined single-pass capture and inactivation efficiency of approximately 98% (i.e., the incremental benefit of adding an 85% efficient device is only 13%). Situations involving ventilation, filtration, and UVC can be evaluated quantitatively by analyzing the entire system.

An example of this type of analysis was given by Nazaroff and Wechsler (2009) for several common arrangements of air cleaners in combination with ventilation. The performance of an air cleaner added to a system with ventilation is defined in terms of an effectiveness ε, which is the difference in contaminant concentration in a space of interest caused by adding an air cleaner and the concentration that would exist without the air cleaner:

$$\varepsilon = \frac{C_{baseline} - C_{control}}{C_{baseline}} \quad \textbf{(12)}$$

where $C_{baseline}$ is the concentration without the air cleaner and $C_{control}$ is the concentration after addition of the air cleaner. This performance measure would show, for example, that adding UVC to a system with a low ventilation rate would have a higher effectiveness (i.e., greater impact) than adding the same device to the same system with a higher ventilation rate. The extension of this concept to multiple-space systems and multiple air cleaners and air cleaner types

is straightforward. System designers can use such methods to obtain more accurate cost/benefit estimates and to optimize the characteristics and placement of air cleaners.

Even in the absence of the constraints imposed by building codes, the system designer should consider the potential benefits of combining air treatment methods. For example, the cost of particulate filters and their negative impact on fan energy use increase in inverse relation to the sizes of particles to be controlled (i.e., filters for smaller particles tend to be more expensive and have higher pressure drop than filters for larger particles). On the other hand, many larger microorganisms that may be resistant to UVC, such as some fungal spores, can be captured effectively by filters of moderately high efficiency and cost (Kowalski 2009). In addition, using UVC to suppress microbial growth on filters that capture but do not kill is a potential complementary use of these two technologies. Ultimately, the decision to use or not use one of the available, effective microbial control methods should be based on a complete analysis that considers overall performance goals for air quality, impact on energy use, and economic factors. Such an analysis is illustrated for a typical air disinfection system by Lee et al. (2009), as discussed in the following section.

5. ENERGY AND ECONOMIC CONSIDERATIONS

The major costs of owning and operating a UVC system include initial equipment and installation costs, maintenance costs (primarily lamp replacement), and energy cost (direct cost of lamp operation plus impact on heating and cooling energy consumption). For a given system, these costs are relatively straightforward to estimate. The benefits of a UVC system are not so easily quantified. Energy use is of concern, and it is also the major operating cost component of most systems. Considerations of energy conservation measures inevitably lead to the issue of cost effectiveness. Therefore, it is appropriate to discuss energy use in conjunction with its economic impact.

Air treatment systems and room surface disinfection systems have the objective of improving the safety, health, and productivity of building occupants through reduced incidence of infectious disease and sick building complaints. Although many studies exist to support claims of UVC's effectiveness in these applications, it is difficult to express the resulting benefits in economic terms. A conservative approach to economic evaluation is to compare the costs of alternative approaches such as dilution ventilation and particulate filtration that have the same effectiveness.

When alternative systems are compared with UVC, all associated costs must be carefully estimated. Increased ventilation adds to heating- and cooling-coil loads and may also affect fan energy use. Particle filtration systems have their own associated installation and maintenance costs and may significantly increase air-side pressure drop and, therefore, fan energy consumption.

Cooling-coil treatment systems have the two-fold objectives of maintaining coil performance and minimizing energy use by reducing air-side flow resistance and increasing the overall heat transfer coefficient relative to a conventionally maintained, mechanically and chemically cleaned coil.

Field studies in the United States (Bahnfleth and Firrantello 2017; Firrantello and Bahnfleth 2017a) and Singapore (Wang et al. 2016a, 2016b) in hot, humid climates report significant improvements in air-side pressure drop and heat transfer coefficient. A system in Tampa, FL, experienced a 22% reduction in pressure drop and 15% increase in air-side heat transfer coefficient after less than two months of surface treatment system operation. Similar results were obtained from a system in Singapore. Improvement in heat transfer coefficient of the Singapore system cooling coil (Wang et al. 2016b) resulted in a chilled-water flow rate reduction of 8.0 to 11.9% and an increase in chilled-water temperature difference of 0.4 to 0.6 K. Changes in performance in drier climates were less dramatic, as indicated by a laboratory study in Colorado (Luongo et al. 2017; Luongo and Miller 2016) and field data from a system in State College, PA (Bahnfleth and Firrantello 2017). As in the case of air disinfection systems, costs to install and operate coil treatment systems are easily estimated, but though there are many reports of significant improvement in performance, there are relatively few peer-reviewed studies documenting its real-world performance (summarized by Bahnfleth 2017).

Economic analysis of UVC coil treatment based on field measurements (Firrantello and Bahnfleth 2017b; Wang 2017) indicates that energy consumption of germicidal lamps is less than corresponding savings in fan, chiller, and pump energy. However, annual energy savings vary greatly between hot, humid climates where coils are continuously wet and temperate ones in which coils may be dry or inactive for several months per year. Thus, cost effectiveness of coil treatment based on energy savings alone is not certain. Economic performance appears much more favorable when reductions in maintenance cost and improvements in air quality are included in the analysis. Firrantello and Bahnfleth (2017c) modeled effects of air disinfection by a coil treatment system on sick leave for six typical buildings in 16 climate zones. They found that, although typical sizing practices for coil UVC systems only reduced illness-related costs by 3.5%, the monetized value of this improvement was 20 times the energy cost to operate the system.

Upper-Room UVC Devices

The effectiveness of upper-room UVC performance has often been described in terms of equivalent air changes per hour (eACH): that is, by the rate of outside airflow measured in room volumes per hour that would achieve the same reduction of microbial air contamination in a well-mixed space. Riley et al.'s (1976) study of UVGI efficacy found that one 17 W UVC lamp covering 18.6 m^2 produced 10 equivalent ACH versus a natural die-off of 2 ACH when a surrogate for tuberculosis was released in the room. The UVC lamp took less than 20 min to inactivate the bioaerosol, versus over 30 minutes for a natural die-off. In a bioaerosol room study, McDevitt et al. (2008) showed seasonal variations of between 20 to 1000 equivalent ACH for a surrogate for smallpox. Ko et al. (2001) modeled the cost of using three air-cleansing strategies to control transmission of tuberculosis in a medical waiting room. They calculated a present value per avoided tuberculin skin test conversion (evidence of infection) of $1708 for increased ventilation, $420 for HEPA

filtration, and $133 for upper-room UVC: that is, UVC was less expensive by a factor of 3 to 13. Another metric is cost to provide a typical level of treatment per unit of floor area. The estimated health care benefit, typical of such analyses, was much larger than the cost: roughly $430/m^2 per year.

In-Duct Air Disinfection

Bahnfleth et al. (2009) and Lee et al. (2009) used simulation to investigate the energy use and operating cost of in-duct UVC air treatment applied upstream or downstream of the cooling coil in a cooling-only variable-air-volume system located in New York and compared it with equivalent added particulate filter. A representative MERV 12 filter (based on ASHRAE *Standard* 52.2-2017) was estimated to provide the same performance as UVC designed for 85% single-pass inactivation under design conditions. They computed not only the costs associated with the alternatives considered, but also estimated the health benefit using a method based on the Wells-Riley equation as applied by Fisk et al. (2005). They found that locating the UVC system upstream of the cooling coil in the normally warmer mixed-air section of the air-handling unit reduced its required size by roughly 50% relative to a downstream location using typical in-duct lamp characteristics. Annual energy cost at an average electric rate of $0.10/(kW · h) ($0.03/MJ) was approximately $0.22/m^2 for the downstream location and $0.11/m^2 for the upstream location, whereas the additional MERV 12 filter cost $1.08/m^2. Annualized life-cycle cost, including installation and maintenance, was $7.97/m^2 for the downstream location, $4.09/m^2 for the upstream location, and $19.27/m^2 for MERV 12 filtration. The drawback to the more economically advantageous upstream UVC location is that it is considered a less favorable location for cooling coil irradiation, which many air treatment systems are designed to do as a benefit of increased airflow and heat exchange efficiency and reduced coil cleaning.

Upper-Room Versus In-Duct

Economic factors clearly favor an upper-room luminaires when the building being treated with UVC has no air distribution system. When a recirculating central air distribution system is present, a choice becomes possible between upper-room devices, which must be distributed throughout occupied spaces, and in-duct systems, which can be centralized. As noted in the preceding discussion of in-duct systems, an annual operating cost of $0.11 to $0.22/m^2 is possible at an electric rate of $0.10/kW · h ($0.03/MJ). The same study (Lee et al. 2009) estimated an installed cost for equipment of $1.40 to 2.69/m^2. By comparison, a typical upper-room system might cost more than $43.05/m^2 to install and more than $1.07/m^2 to operate, based on typical sizing procedures and current equipment costs. This comparison seems to strongly favor in-duct systems where they are applicable but is based on an assumption of equal performance that may not be valid. In a health care setting, controlling transmission of airborne pathogens at their source would suggest an upper-room approach. However, where feasible, a whole-building approach to UV should be considered.

Cooling Coil Surface Treatment

Cooling coil surface treatment is done as an alternative to periodic mechanical and chemical cleaning of coils. By suppressing the formation of biofilms and mold growth on coils, coil irradiation should reduce air-side pressure drop, increase heat transfer coefficient, and reduce both fan and refrigeration system energy consumption. Several studies have documented the ability of coil irradiation to reduce microbial growth (Levetin et al. 2001; Shaughnessy et al. 1998). No peer-reviewed studies have yet been published to document the effect of coil irradiation on energy consumption, but there are many strong anecdotal reports of its effectiveness. As noted previously, the U.S. General Services Administration has sufficient confidence in this application to include it in its mechanical requirements (GSA 2018).

6. ROOM SURFACE TREATMENT

Environmental contamination in health care settings and transmission of health-care-associated pathogens to patients occurs most frequently via contaminated hands of health care workers and transmission of pathogens to patients (Boyce 2010). A primary concern in health care settings has been reducing nosocomial infections and finding new approaches for these environments to help eliminate infections from health care settings. Hospital-acquired infections generate a high financial burden for the health care industry and the consumer, costing the U.S. health care system billions of dollars each year. According to the U.S. Department of Health and Human Services (U.S. HHS 2009), at any given time, about 1 in 25 patients has an infection related to care received in hospitals. UVC for surface disinfection, particularly in health care settings, has been applied over the past 25 years to help reduce the number of microorganisms on surfaces, and consequently UVC should contribute to a reduction in these healthcare-acquired infections (HAIs). It is important to note that UVC serves as an adjunct cleaning technology and not as a replacement of traditional cleaning methods that follow APIC and AORN guidelines. Scientific studies have shown reductions in viable infectious agents on surfaces after UVC exposure; however, methods of testing for various portable UVC devices (also called UVC robots) still need to be developed to provide proper performance guidance to the consumer.

Various portable UVC devices have been deployed in health care settings, which can easily be moved into patient rooms, surgical suites, ICUs, and other critical care areas that need surface and air disinfection during in-between-case cleaning or terminal cleaning process, or when a patient is diagnosed with a disease transferred by pathogens. Some of the pathogens of interest and their reduction in health care settings are multidrug resistant, such as methicillin-resistant *Staphylococcus aureus* (MRSA), *Clostridiodes difficile*, *Acinetobacter baumannii*, and vancomycin-resistant *Enterococci*

(VRE). These pathogens can be inactivated by proper application of UVC energy. Several UVC studies have shown the effectiveness of whole-room disinfection devices in inactivating commonly found pathogens and decreasing the resulting HAIs in hospitals (e.g., Weber et al. 2016). Reputable mobile UVC devices will have third-party testing for specific pathogens and are registered with the EPA under the *Federal Insecticide, Fungicide, and Rodenticide Act* (EPA 2013).

UVC fixtures can also be installed in surgical suites to disinfect surfaces and air in between or during procedures, or for terminal cleaning after all standard cleaning protocols have been performed. A 19-year study on UVC during orthopedic surgery showed that 47 infections occurred following 5980 joint replacements. The infection rates for total hip replacements decreased from 1.03% to 0.72% (p = 0.5407), and for total knee replacements from 2.20% to 0.5% (p < 0.0001). The study concluded that UVC appears to be an effective way to lower the risk of infection in the operating room during total joint replacement (Ritter et al. 2007). Safety precautions must be followed when applying UVC during surgery to protect workers from accidental exposure (see the following discussion of intensity of source) or upper air fixtures may be used as discussed previously. Tools and instruments used in health care applications can be disinfected with UVC after regular cleaning; however, depending on application, this may fall under the FDA regulatory body as a medical device. UV irradiation does not replace sterilization of surgical instruments.

UVC surface disinfection is also applied in schools, morgues, nursing homes, and homeless shelters: surfaces can be irradiated with fixed or mobile UVC devices that serve as part of the room's disinfection methodology.

Application of UVC to any surface is based on the UV dose delivered to the surface. The dose (μJ/cm^2) of UVC needed to disinfect a surface depends on the selected target organism and desired disinfection level. Different microorganisms require various levels of UVC intensity for inactivation (see Figure 4). Vegetative forms of bacteria tend to be more susceptible to UVC energy than spore-forming microorganisms. UVC irradiates all line-of-sight objects and partially into shadowed areas (e.g., tables, chairs, surgical equipment, objects) through reflection, so the desired level of disinfection can be achieved, even on surfaces which are not directly irradiated. Different materials absorb and reflect UVC energy at different rates, depending on the overall reflectivity of the materials, irradiation time, and intensity. UVC surface disinfection should only be applied as an adjunct to normal surface cleaning procedures of the facility. No living organisms, including animals and plants, should be in the room when UVC is deployed.

The same principles as for in-duct applications apply here. There are two primary methods of UVC delivery: direct (line of sight) and indirect (reflection). Most surface applications use a direct source, where the source (typically a mercury vapor lamp) is contained in an assembly designed to direct the UVC energy at a particular surface or in a particular direction with no impedance to the energy beam. In an indirect application, the energy is reflected onto a surface using a reflective material. The reflected UVC energy can be measured to determine accurately when a given amount of the UVC dose has been delivered to the desired target.

The basics of determining the radiant energy levels to a surface are as follows:

Length of exposure. When disinfecting surfaces, it must be first determined if the target is moving or stationary. This helps to identify if there are any limiting factors associated with the length of exposure time. In most surface disinfection applications, time is relative to intensity, meaning that increasing the intensity of the source can decrease the exposure time necessary. It is important to remember that microorganisms vary, requiring a higher or lower intensity for inactivation, depending on their structure (Brickner et al. 2003).

Intensity of source. UVC lamp and equipment manufacturers normally provide the intensity of a given source (lamp or fixture) at a given distance. A distance correction factor may be needed when calculating a desired dose or intensity for a surface. UVC energy follows the same inverse square law for intensity as visible energy and other electromagnetic sources: the amount of energy at the surface is measured in proportion to the square of the distance from the energy's source (UVC lamp), assuming no loss through scattering or absorption. Temperature and airflow corrections may also be necessary, depending on the location of the application. The intensity of a source is given in power per unit area (i.e., μW/cm^2).

Distance from source to surface. In a point irradiation application, the distance is relatively easy to calculate. Calculating time requirements and intensity levels for a three-dimensional object or space is more complex. The varying distances from the source are the first challenge, because the object itself creates a shadowing effect, and any shadows from the local environment must be taken into consideration. However, portable devices are available that can measure the reflected dose from shadowed areas.

Studies on in-room UVC disinfection devices have shown that UVC can be successfully applied to reduce microbiological loads of surfaces located in shadowed areas in addition to line of sight (Rutala 2009). The reductions were up to 4-log for organisms such as MRSA, VRE, *Acinetobacter*, and *C. difficile*. Furthermore, it was concluded that UV room decontamination with the test device reduced colony counts of pathogens by greater than 99.9% within 20 min. Note that, depending on the portable or stationary UVC device, performance could greatly differ with respect to irradiation time, because overall dose delivered to surfaces is the critical measure of portable device performance.

7. OTHER UV-RELATED TECHNOLOGIES

UVC LEDs

Light-emitting diodes (LEDs) are semiconductor devices made of multiple layers of substrate material. Several companies are producing LEDs that emit in the longer-wavelength portion of the UVC region, generally at 265 to 275, nm but some are being made and sold that output at 255 nm. UVC LED technology benefits such as instant start/stop, low-voltage supply, portability, DC or battery power, and mercury-free safety have made LED-based systems attractive

for many existing and new applications. However, compared to traditional mercury-based UV lamps, UVC LEDs are low-power devices, with lower wall-plug efficiencies. LEDs in the UVC range have been shown to be effective at inactivating bacteria and viruses. Where validated, UVC LEDs could be used for both targeted surface disinfection, including cooling coils and upper room air disinfection.

Far UVC

Far UVC technology is an emerging technology that uses excimer light sources emitting a spectral output within the UVC band in the 200 to 230 nm range. The most common far UVC sources are krypton chloride excimer (KrCl*) lamps, which emit polychromatic radiation across a wide segment of the UVC range (Sosnin et al. 2015). They typically exhibit a dominant peak at 222 nm and often a long wavelength tail extending to 200 nm and below, and higher-wavelength emissions extending to ~300 nm and above. Radiation at longer wavelengths can be problematic in terms of human eye and skin exposure risks, while shorter wavelengths can be problematic due to potential ozone generation. As such, most practical applications of KrCl* should include optical filters to minimize contributions of radiation from wavelengths significantly longer or shorter than the peak centered at 222 nm.

KrCl* lamps, like other excimer sources, consume considerable power to generate the dielectric discharge and therefore their wall plug efficiencies are substantially lower than low pressure mercury lamps.

Efficacy. Laboratory studies have shown KrCl* lamps can inactivate microorganisms at comparable rates to conventional low-pressure mercury 254 nm lamps (Buonanno 2020; Beck 2014; Clauss 2009; Matafonova 2008). The two technologies share common disinfection mechanisms, where direct photolysis of DNA/RNA inactivates the target pathogen (Setlow 2020). Wavelengths below 230 nm are expected to be effective for inactivation due to the absorbance of photons by both nucleic acids and proteins; however, these wavelengths have been less widely researched, presumably because of the difficulty in finding UVC sources operating at this region. Though the efficacy of far UVC radiation has been demonstrated in laboratory studies, validation of its performance in field applications is still lacking.

Safety. Current research indicates that the far UVC spectrum can deactivate bacteria and viruses without significant damage to eukaryotic cells (Buonanno 2017; Narita 2018; Niikura 2020; Yamano 2020). This is based on the reported inability of far UVC to penetrate deep into cells, with an expected penetration of approximately 1µm in size (Buonanno 2013). Though more work is required, the evidence suggests the absence of conventional skin and eye damage indicators that would typically result from UVGI, thus offering the potential of using this technology in occupied spaces within reasonable exposure limits. However, no clinical or long-term studies of human exposure and carcinogenicity have been conducted to date and the effect on injured skin or eyes is unknown. The exposure of humans to ultraviolet radiation is the subject of numerous regulations and standards worldwide: 2006/25/EC (Europe), ACGIH 2008 TLVs and BEIs (USA), and IEC 62471 (CB Scheme, global), which define an upper human exposure limit of 23 mJ/cm^2 over an 8 h period. These exposure limits are in the process of review and therefore current limits should be verified prior to the design and use of far UVC light for any applications.

Ozone generation by far UVC sources is a due concern, resulting from photochemical and corona discharge processes and depends on the UV power, air flow/stagnation, operation duty cycle, UV spectrum, etc. Accordingly, risk of ozone exposure should be included in an overall evaluation of safety for far UVC irradiation in the presence of humans.

Photocatalytic Oxidation (PCO)

Photocatalytic oxidation (PCO) technology has generated interest with respect to indoor air applications as it has been shown in studies to improve the indoor air quality by breaking down volatile organic compounds (VOCs), odors, and gaseous contaminants (ASHRAE 2018).

When a photocatalyst such as titanium dioxide (or metal oxides and metal sulfides with sufficient band gap energies) is irradiated with UV light of a certain wavelength (254 to 365 nm), a photochemical reaction takes place on the catalyst surface, forming reactive hydroxyl radicals and superoxide ions in the presence of oxygen and water vapor. These powerful oxidants undertake a series of reactions called photocatalytic oxidation (PCO), involving bond cleavage, substitution, and electron transfer, thereby converting organic pollutants into harmless carbon dioxide and water (Peral and Ollis 1992). More detail about PCO technology is available in the ASHRAE position document on filtration and air cleaning (ASHRAE 2018) and Chapter 47 of this volume.

Although the photocatalyst can be activated in the 254 to 365 nm wavelength range, using UVC lamps or LEDs provide the additional germicidal benefit of inactivating biological contaminants as well. Numerous studies have demonstrated the effectiveness of PCO technology against organic, gaseous indoor air contaminants and microbes (Alberici and Jardim 1997; Dalrymple et al. 2010; Hodgson et al. 2007; Zhong et al. 2013). Conversion efficiencies of PCO air cleaners depend on the design of the device, operating environment (e.g., airflow, relative humidity, temperature), cleanliness of the photo-catalyst material, and the nature and concentration of the contaminants (Destaillats et al. 2012). There are market-available PCO systems that use the UVV (100 to 200 nm) lamp that will produce ozone. These devices should be tested for ozone emission as detailed in the air cleaning documents (ASHRAE 2018; Chapter 47 of this volume)

One of the considerations for applications of the PCO technology is the potential formation of byproducts in the event of incomplete oxidation. Limited work has been conducted to explore the impacts of operational conditions, including the presence and absence of ozone, photocatalyst types, UV lamps, initial concentration, and water vapor on the distribution and production of byproducts (Zhong and Haghighat 2015).

405. nm Violet Visible Light

Although outside of the UVC wavelength, 405 nm violet visible light, sometimes referred to as indigo light, is an emerging disinfection light-based technology with spectral output between the visible and UV wavelengths primarily in the 400 to 420 nm range. Blue-violet light is generated by light-emitting diode LEDs, phosphor-coated LEDs, or low-pressure mercury lamps.

The germicidal effects of visible light have been demonstrated for wavelengths from approximately 380 nm to 480 nm, but peak efficacy has been demonstrated at approximately 405 nm (e.g., Hessling et al. 2017; Maclean et al. 2008; Tomb et al. 2018). Its inactivation mechanism differs from germicidal UVC light wherein the 405 nm light does not have sufficient energy to disrupt DNA or RNA. Bacteria, fungi, and protozoa contain intracellular (endogenous) porphyrins that strongly absorb visible light around 405 nm. These porphyrin molecules consequently transfer the photon's energy to an oxygen molecule within the cell, producing a **reactive oxygen species (ROS)** molecule, such as singlet oxygen or hydrogen peroxide, that is highly reactive and cytotoxic (Kumar et al. 2015; Ramakrishnan et al. 2009). It is the ROS that inactivates the cell by disrupting its cellular machinery (Plavskii et al. 2014).

Whether viruses and bacteriophages (viruses that infect bacteria) are susceptible to visible light is a topic of ongoing research (Hessling et al. 2022). It has been argued that they should not be because they do not contain porphyrins or other endogenous photosensitizers that are capable of generating reactive oxygen species (ROS).

The peer-reviewed literature has validated the germicidal properties of 405 nm blue-violet visible light in the laboratory setting, and observational clinical trials have been published on biofilm reduction. The limited published studies on the efficacy of visible light suggest that the range of light doses needed for inactivation can be enormous (Bache et al. 2017; Maclean et al. 2014; Rutala et al. 2018). A major drawback is that no validated test method has been established by any standards-setting body to test the 405 nm output delivered at the surfaces with which it contacts. There are also some concerns about the health effects related to 405 nm similar to health effects from strong doses of sunlight. It has been reported that exposure to 400 to 500 nm blue light with high doses may result in skin pigment darkening and pose a risk to people with photosensitive diseases, or who are taking photosensitizing drugs (Christensen et al. 2021). Although some manufacturers claim that their violet-blue light fixtures are exempt from IEC 62471 for photobiological safety, users should aware that exposure limits are dependent on the spectral wavelength output and should verify if the fixtures confirm to available international standards (ACGIH 2015; ICNIRP 2013)

8. SAFETY

Hazards of Ultraviolet Radiation to Humans

UVC is a low-penetrating form of UV compared to UVA or UVB. Measurements of human tissue show that 4 to 7% of UVC (along with a wide range of wavelengths, 250 to 400 nm) is reflected (Diffey 1983) and absorbed in the first 2 μm of the stratum corneum (outer dead layer of human skin), thus minimizing the amount of UVC transmitted through the epidermis (Bruls 1984).

Although UV is far more energetic than the visible portion of the electromagnetic spectrum, it is invisible to humans. Therefore, exposure to ultraviolet energy may result in transient corneal inflammation, which can go unnoticed.

Ocular damage generally begins with **photokeratitis** (inflammation of the cornea) but can also result in **photokeratoconjunctivitis** (inflammation of the conjunctiva [ocular lining]). Symptoms, which may not be evident until several hours after exposure, may include an abrupt sensation of sand in the eyes, tearing, and eye pain, possibly severe. These symptoms usually appear within 6 to 12 h after UV exposure and resolve fully within 24 to 48 h. Acute overexposure to UVC radiation may cause some incapacity due to eye discomfort, but this generally abates after several days, leaving no permanent damage.

Cutaneous damage consists of erythema, a reddening of the skin akin to sunburn (but without tanning). The maximum effect of erythema occurs at a wavelength of 296.7 nm in the UVB band. UVC radiation at a wavelength of 253.7 nm is less effective in causing erythema. Because ultraviolet radiation is carcinogenic, questions have been raised concerning open-air UVC systems. The International Commission on Illumination (CIE) completed a review of UVC photocarcinogenesis risks from germicidal lamps using basic biophysical principles: because of the attenuation provided by the stratum corneum and epithelial tissues of the skin, upper-room disinfection can be safely used without significant risk for long-term delayed effects such as skin cancer (CIE 2010).

Sources of UV Exposure

UVC energy does not normally penetrate through solid substances and is attenuated by most materials. Quartz glass, soda barium glass, and TFPE plastic have high transmissions for UVC radiation.

UVC energy can reflect from most metals and several types of painted and nonpainted surfaces; however, a surface's ability to reflect visible light cannot be used to indicate its UV reflectance. The fact that a blue glow can be observed on a metal surface from an operating low-pressure UV fixture lamp could indicate the presence of UV, and a measurement should be performed to ensure there is no exposure risk.

Well-designed and commissioned UVC installations, education of maintenance personnel, signage, and use of safety switches can help to avoid overexposure. During commissioning and before operation of the UVC installation, hand-held radiometers with sensors tuned to read the specific 254 nm wavelength should be used to measure stray UVC energy and should be used in upper-room systems.

Exposure Limits

In 1972, the Centers for Disease Control and Prevention (CDC) and National Institute for Occupational Safety and Health (NIOSH) published a **recommended exposure limit (REL)** for occupational exposure to UV radiation. The REL is intended to protect workers from the acute effects of UV exposure, although photosensitive persons and those exposed concomitantly to photoactive chemicals might not be protected by the recommended standard (NIOSH 1972).

Exposures exceeding CDC/NIOSH REL levels require that workers use personal protective equipment (PPE), which consists of eyewear and clothing known to be nontransparent to UVC penetration and which covers exposed eyes and skin.

UV inspection, maintenance, and repair workers typically do not remain in one location during their workday, and therefore are not exposed to UV irradiance levels for 8 h. Threshold Limit Value® (TLV®) consideration should be based on real-time occupancy of spaces treated by UVC (ACGIH 2007; Sliney 2013). This recommendation is supported by UV monitoring data from First et al. (2005), which showed that peak meter readings poorly predict actual exposure of room occupants.

Evidence of Safety

During the height of the tuberculosis resurgence in the United States in the 1990s, the Tuberculosis Ultraviolet Shelter Study (TUSS), a double-blind, placebo-controlled field trial of upper-room UVC, was conducted at 14 homeless shelters in six U.S. cities from 1997 to 2004 (Brickner et al. 2000). Following available recommended placement, installation, and maintenance guidelines, each building in the study was evaluated for treatment with upper-room UVC fixtures. At the conclusion of the study, the safety of room occupants was evaluated using data from a total of 3,611 staff and homeless study subjects regarding eye and skin irritation. Analysis showed no statistically significant difference in the number of reports of symptoms between the active and placebo periods. There was one definite instance of UV-related photokeratoconjunctivitis (from eye overexposure). This occurred from a placement of an elevated bunk bed in a dormitory where a single bed had been used when the UV fixtures were first installed. By moving the UV fixture, this incident was resolved (Brickner and Vincent 2013). This study demonstrated that, with careful application, side effects of UV overexposure can be avoided. Because of the enclosed nature of in-duct UVC systems, with careful adherence to safety guidelines, these systems should not result in UV exposure.

Because in-duct UVC systems are installed inside air-handling units or ventilation ductwork, typical building occupants are not expected to be exposed to UV energy. On the other hand, building facilities workers and maintenance personnel are at risk of high UV exposures with in-duct systems. To minimize the risk to these workers, UVC systems should be designed with specific safety features and all workers that could potentially work around the UV fixtures should receive UV-specific training.

Safety Design Guidance

Upper-room systems should have on/off switches and an electrical disconnect device on the louvers. If UV radiation measurements at the time of initial installation exceed the recommended exposure limit, all highly UV-reflecting materials should be removed, replaced, or covered. UV-absorbing paints containing titanium oxide can be used on ceilings and walls to minimize reflectance in the occupied space.

Warning labels must be posted on all upper-room UV fixtures to alert personnel to potential eye and skin hazards. Damaged or illegible labels must be replaced as a high priority. Warning labels must contain the following information:

- Wall sign for upper-room UVC **Caution:** Ultraviolet energy. Switch off lamps before entering upper room.
- General warning posted near UVC lamps. **Caution:** Ultraviolet energy. Protect eyes and skin.

Upper-room UVC fixtures can vary widely in their luminaire efficiency factors, which rates the performance of emitted UVC from a fixture. Zhang et al. (2012) developed a protocol and performed gonioradiometric measurements (i.e., measuring both radiance and irradiance at concurrent angles) for upper-room UVGI fixtures, which is now being used to test total UVC fixture output (Leuschner and Salie 2013). These gonioradiometric measurements are reported in standard IES format compatible with computer-aided design (CAD) lighting software adapted for use with upper room UVC devices (Rudnick et al. 2012; Vincent et al. 2013).

In-duct systems should be fully enclosed and sealed to prevent leakage of UV radiation to unprotected persons or materials outside of the HVAC equipment. The fifth edition of UL *Standard* 1995 requires that no opening permit leakage of UVC greater than 0.1 $\mu W/cm^2$, and that points of intentional access to UV sources must be equipped with an interlocking mechanism that deenergize the UV source. All access panels or doors to the lamp chamber and panels or doors to adjacent chambers where UV radiation may penetrate or be reflected should be interlocked and have warning labels posted in appropriate languages. Labels should be placed on the outside of each panel or door, in a prominent location visible to people accessing the system. At a minimum, the labels should state

- General warning posted near UVGI/UVC lamps **Caution:** Ultraviolet energy. Protect eyes and skin.
- Multilingual warning posted on the door of air handlers where UVC is present in ductwork. **Caution:** Ultraviolet energy in duct. Do not switch off safety button or activate lamps with door open.

Lamp chambers should have door safety interlock switches and electrical disconnect devices. Disconnection devices must be able to be locked or tagged out, and should be located outside the lamp chamber, next to the chamber's primary access panel or door. Switches should be wired in series so that opening any switched access deenergizes the system. It is recommended that on/off switches for UV lamps not be located in the same location as general room lighting; instead, they should be in a location that only authorized persons can access and should be locked or password protected to ensure that they are not accidentally turned on or off.

The lamp chamber should have one or more viewports of UVC-absorbing materials. Viewports should be sized and located to allow an operating UV system to be viewed from outside of the HVAC equipment.

9. INSTALLATION, START-UP, AND COMMISSIONING

The operating instructions and advice of UVC system designers and lamp manufacturers should always be followed to ensure the proper operation of any UVGI/UVC system. It is important to operate any such system within the temperature and relative humidity ranges considered during the system design process. The following section presents some general guidelines for initially verifying and maintaining adequate system performance.

Upper-Room UVC Devices

Those responsible for the commissioning process should inspect fixture placement and eye level irradiance measurements using a 254 nm selective radiometer. UVC levels can be measured with a UV radiometer directly facing the device at eye height at various locations in a room and must be taken in the same location each time. UVC measurements should be taken at eye level (between 1.68 and 1.83 m) at compass points from each figure. Check reflective surfaces (e.g., TVs, monitors). Software can be used to preview safety of UVGI/UVC upper room installations (Vincent et al. 2013). Incorporate readings into final commissioned drawings. If the readings indicate an eye-level exposure that exceeds the 8 h TLV for UVC of 6 $\mu J/cm^2$, the UV systems must be deactivated until adjustments can be made or the manufacturer can be contacted. Measurements should be made at initial installation, whenever new UV lamps are installed (newer lamp designs may provide increased irradiance), and whenever modifications are made to the UVC device or room (e.g., adjusting fixture height, relocating or repositioning louvers, adding UV-absorbing or -reflecting materials, changing room dimension or modular partition height).

In-Duct UVC Systems

Installation, start-up, and commissioning of in-duct UVGI systems are straightforward. Those responsible for installation should ensure that the system is installed as designed and that all lamps, ballasts, and/or fixtures are the same as included in the final design. Take care to ensure that all safety interlocks and view ports are installed in appropriate positions and functional. Once the UV lamps are powered on, ensure that all lamps are burning. Unfortunately, there are no good methods for in situ testing of in-duct system performance, so relying on final design parameters is essential to ultimate system performance.

10. MAINTENANCE

All UVC systems require periodic inspection, maintenance, and lamp replacement to ensure proper system performance. Whenever maintenance is performed on UVC systems, the appropriate safety guidelines outlined elsewhere in this chapter should be carefully followed.

Material Degradation

UVC energy can be detrimental to most organic materials. If the UVC is not applied properly and sensitive materials are not shielded or substituted, degradation can occur. However, the degradation may not be enough to cause failure of the material if UVC only penetrates micrometers into the material before the degradation plateaus off, leaving a still fully functional material, as found by ASHRAE research project RP-1509, sponsored by TC 2.9 (Kauffman 2010). Air filters are known to be sensitive to degradation by UVC, especially those made from synthetic materials. Glass fibers by themselves are unaffected by UV exposure, but binding materials in glass fiber filters may be degraded. As a general rule, synthetic air filters should not be exposed to UVC.

Lower doses, or those typically sized for cooling coil surface treatment, of UVC exposure to organic materials resulted in much slower rates of degradation (Kauffman 2017). Although UVC photodegradation is of concern, with the selection of the proper material or metallic shielding of components, the problem is significantly reduced, and components can be expected to meet product design life. As a simple, practical approach, it is wise to shield all organic material components within about 1.5 m of the UV lamp. Some indoor plants do not tolerate prolonged UVC exposure and should not be hung higher in the room where upper air UVC devices are installed.

Visual Inspection

Maintenance personnel should routinely perform periodic visual inspection of the UVC lamp assembly. Typically, a viewing port or an access door window is sufficient for in-duct applications. Closer visual inspection may be required for upper-room systems because a single burned-out lamp in a multilamp fixture may not be apparent from the lower room. Personal protective measures are required for this close-up inspection.

Any burned-out or failing lamps should be replaced immediately. If lamps become dirty in dusty environments, they should be cleaned with a lint-free cloth and isopropyl alcohol. Care should be taken to ensure no film remains on the surface of the lamps after cleaning. This film could reduce UV output from the lamp. Complete lamp fixtures should be replaced whenever they are visibly damaged or in accordance with manufacture warranty guidelines.

UV Measurement: Radiometers and Photochromatic Ink

There are multiple ways to measure and quantify both UVC intensity and UVC dose. A **radiometer** or **photometer** with a UVC responsive sensor is the most accurate. Some (not all) radiometers can provide the user with a UVC intensity reading as well as a UVC dose. Depending on the application, the user should select the device according to their needs. It is important to consider a manufacturer that offers a radiometer model that can be recalibrated as needed, with traceability to a known standard. Radiometers can range in price from a few hundred dollars to a few thousand, depending on features, resolution, and sophistication. Most radiometers have two basic components: the base unit with an analogue or digital display and a sensor module. These sensor modules can be built into the base unit, tethered via a communications cable, or can report back to the base via a wireless method. Sensors can have different response curves or allow different band pass ranges; this is important when comparing measurements between different devices and models. Consult the technical data information provided by the manufacturer to confirm that the proper wavelength sensitivity is selected for the desired data collection.

Another method used to quantify UVC surface dose is the use of a **photochromatic ink indicator**, usually printed on a label or paper to be affixed to a target surface. These are commonly referred to as **dosimeters**. Dosimeters typically show a change in color when the photochromatic ink is exposed to a certain dose of UV. In some cases, as the cumulative dose increases the color change may continue, indicating a higher dose has been delivered. The reactive dose varies based on the photo-initiator concentration and other components of the chemistry. The colors can vary, and most dosimeter manufacturers will provide a gauge to allow the user to estimate the dose, which does make using a dosimeter somewhat subjective. Photochromatic ink indicators are available from multiple manufacturers and compared to radiometers they are relatively inexpensive, but the end user will sacrifice accuracy compared to radiometers. The accuracy of the photochromatic ink varies based on the manufacturer, and the user should consider the application and accuracy required when considering this type of indicator. Reusable indicators are also available from various manufacturers, which offer cost savings and waste reduction compared to one-use indicators.

Lamp Replacement

UVC lamps should be replaced at the end of their useful life, based on equipment manufacturer recommendations or radiometer measurements. Where applicable, it may be prudent simply to change lamps annually (8760 h when lamps are run continuously) to ensure that adequate UV energy is supplied by a given system. Lamps can operate after their useful life, but at reduced performance, and require regular measurement to ensure that a maintained level of UVC is being generated. A blue visible light emitted from the lamp does *not* indicate that UVC is present. The typical rated life of UVC lamps is 9000 h of operation. Switching lamps on and off too often may lead to early lamp failure, depending on the ballast type used. Consult the lamp manufacturer for specific information on expected lamp life and effects of switching.

Lamp and Ballast Disposal

UVC lamps should be treated in the same manner as other mercury-containing devices, such as fluorescent lamps. Some lamps may need to be treated as hazardous waste and not discarded with regular waste, although low mercury lamps may be an exception; however, check state and local codes for proper determination. The U.S. EPA's universal waste regulations allow users to treat mercury lamps as regular waste for transport to a recycling facility (EPA 2018). This simplified process was developed to promote recycling. The National Electrical Manufacturers Association maintains an online list of companies claiming to recycle or handle used mercury lamps (NEMA 2009). The most stringent of local, state, or federal regulations for disposal should be followed.

UVC systems currently depend on the use of an electronic ballast to provide the UV lamp with power; however, many older systems used magnetic ballasts instead. Magnetic ballasts manufactured before 1979 contain polychlorinated biphenols (PCB) in the dielectric of their capacitors (EPA 2017). Recycling is the best way to dispose of all magnetic ballasts. The process allows the reuse of copper and aluminum wire, steel laminations, and steel cases, and disposes of capacitors and potting compound as hazardous waste in high-temperature incinerators.

Failed electronic ballasts should be treated as electronic waste. Many lamp and ballast recyclers are expanding their businesses and becoming certified to accept electronic waste. Some recyclers now accept both lamps and electronic ballasts.

Personnel Safety Training

Workers should be provided with as much training as necessary, including health and safety training, and some degree of training in handling lamps and materials. Workers should be made aware of hazards in the work area and trained in precautions to protect themselves. Training topics include the following:

- UVC exposure hazards
- Electrical safety

- Lock-out/tag-out (for in-duct units)
- Health hazards of mercury
- Rotating machinery (for in-duct units)
- Slippery condensate pans (for in-duct units)
- Sharp unfinished edges (for in-duct units)
- Confined-space entry (if applicable) (for in-duct units)
- Emergency procedures

Workers expected to clean up broken lamps should be trained in proper protection, cleanup, and disposal.

No personnel should be subject to direct UV exposure, but if exposure is unavoidable, personnel should wear protective clothing (no exposed skin), protective eyewear, and gloves. Most types of eyewear, including prescription glasses, may be sufficient to protect eyes from UV, but not all offer complete coverage. Standard-issue safety goggles or clear full-face masks may be the best alternative.

If individual lamp operating conditions must be observed, this should preferably be done using the view port or window(s).

During maintenance, renovation, or repair work in rooms with upper-room UV systems, all UVC devices must be deactivated before personnel enter the upper part of the room.

For in-duct systems, access to lamps should be allowed only when lamps are deenergized. The lamps should be turned off before air-handling unit (AHU) or fan shutdown to allow components to cool and/or to purge any ozone in the lamp chamber (if ozone-producing lamps are used). If AHUs or fans are deenergized first, the lamp chamber should be opened and allowed to ventilate for several minutes. Workers should always wear protective eyewear and puncture-resistant gloves for protection in case a lamp breaks.

Access to the lamp chamber should follow a site-specific lock-out/tag-out procedure. Do not rely on panel and door safety switches as the sole method to ensure lamp deenergizing. Doors may be inadvertently closed, or switches may be inadvertently contacted, resulting in unexpected lamp activation.

If workers enter the condensate area of equipment, the condensate pan should be drained and any residual water removed.

In general, avoid performing readings with the fan running and workers inside an AHU (e.g., only to test for output reduction caused by air cooling). Tests of this nature should be instrumented and monitored from outside the equipment.

Lamp Breakage

If workers break a lamp, they should warn all other workers to exit the HVAC equipment area. Panels or doors should be left open and any additional lamp chamber access points should also be opened. Do not turn air-handling unit fans back on. After 15 min, workers may reenter the HVAC equipment to begin lamp clean-up.

If a lamp breaks in a worker's hand, the worker should not exit the HVAC equipment with the broken lamp. The worker should carefully set the broken lamp down, and then exit the space. When possible, try not to set the broken lamp in any standing condensate water. Follow standard ventilation and reentry procedures.

Cleanup requires special care because of mercury drop proliferation and should be performed by trained workers. As a minimum, workers should wear cut-resistant gloves, as well as safety glasses to protect eyes from glass fragments. Large bulb pieces should be carefully picked up and placed in an impervious bag. HEPA-vacuum the remaining particles or use other means to avoid dust generation.

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