CHAPTER 17

ULTRAVIOLET LAMP SYSTEMS

UV energy is electromagnetic radiation with a wavelength shorter than that of visible light, but longer than soft x-rays. All UV ranges and bands are invisible to the human eye. The UV spectrum can be subdivided into following bands:

- UV-A (long-wave; 400 to 315 nm): the most abundant in sunlight, responsible for skin tanning and wrinkles
- UV-B (medium-wave; 315 to 280 nm): primarily responsible for skin reddening and skin cancer
- UV-C (short-wave; 280 to 200 nm): the most effective wavelengths for germicidal control
- Radiation below 200 nm is also called vacuum UV and can produce ozone (O_3) in air

Use of ultraviolet (UV) lamps and lamp systems to disinfect surfaces, room air, and airstreams dates to about 1900; see Riley (1988) and Schechmeister (1991) for extensive reviews of UV disinfection. Early work established that the most effective UV wavelength range for inactivation of microorganisms was between 220 to 300 nm, with peak effectiveness near 265 nm.

UV-C energy disrupts the DNA of a wide range of microorganisms, rendering them harmless (Brickner et al. 2003; CIE 2003). Figure 1 shows the relative effectiveness of UV-C energy at various wavelengths to cause DNA damage. Most, if not all, commercial UV-C lamps are low-pressure mercury lamps that emit UV energy at 253.7 nm, very close to the optimal wavelength.

Ultraviolet germicidal irradiation (UVGI) in the UV-C band has been used in air ducts and air-handling units for some time, and its use is becoming increasingly frequent as concern about energy, maintenance, and indoor air quality increases. UV-C energy is used as an engineering control to interrupt the transmission of pathogenic organisms, such as *Mycobacterium tuberculosis* (TB), influenza viruses, mold, and possible bioterrorism agents (Brickner et al. 2003; CDC 2002, 2005; GSA 2003). In addition, it has been used extensively to irradiate air-conditioning cooling coils to maintain cleanliness and provide energy savings.

This chapter includes a review of the fundamentals of UV-C energy's impact on microorganisms; how UV-C lamps generate germicidal radiant energy; various components that comprise UV-C devices and systems; and a review of human safety and maintenance issues.

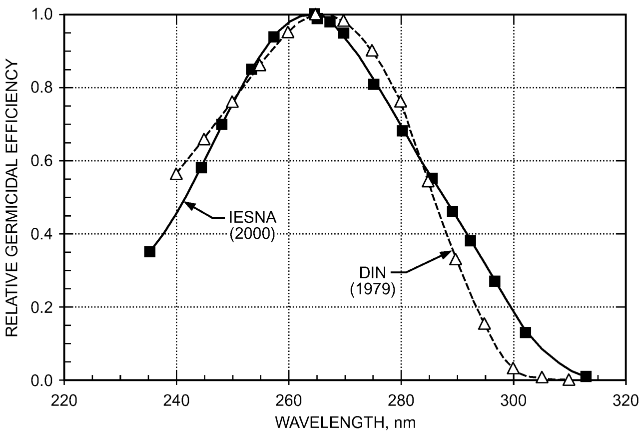

Fig. 1 Relative UV-C Germicidal Efficiency

The preparation of this chapter is assigned to TC 2.9, Ultraviolet Air and Surface Treatment.

1. TERMINOLOGY

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

Droplet nuclei. Airborne particles formed from evaporation of fluids emitted from infected hosts when they cough, sneeze, or talk, containing bacteria or viruses able to transmit disease from person to person. Droplet nuclei generally have an aerodynamic diameter less than 5 μm, which allows them to remain suspended in air for long periods; thus, they can be carried on normal air currents in a room and beyond to adjacent spaces. When inhaled, droplet nuclei can penetrate into the alveolar region of the lung.

Erythema (actinic). Reddening of the skin, with or without inflammation, caused by the actinic effect of solar radiation or artificial optical radiation. See CIE (1987) for details. (Nonactinic erythema can be caused by various chemical or physical agents.)

Exposure. Being subjected to something (e.g., infectious agents, irradiation, particulates, and/or chemicals) that could have harmful effects. For example, a person exposed to *M. tuberculosis* does not necessarily become infected.

Exposure dose. Radiant exposure (J/m^2, unweighted) incident on biologically relevant surface.

Fluence. Radiant flux passing from all directions through a unit area in J/m^2 or J/cm^2; includes backscatter (reflection).

Germicidal radiation. Optical radiation able to kill pathogenic microorganisms.

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 (1987) for details.

Mycobacterium tuberculosis. The namesake member of *M. tuberculosis* complex of microorganisms, and the most common cause of tuberculosis (TB) in humans. In some instances, the species name refers to the entire *M. tuberculosis* complex, which includes *M. bovis*, *M. africanum*, *M. microti*, *M. canettii*, *M. caprae*, and *M. pinnipedii*.

Optical radiation. Electromagnetic radiation at wavelengths between x-rays ($\lambda \approx 1$ nm) and radio waves ($\lambda \approx 1$ mm). See CIE (1987) for details.

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.

Photokeratitis. Defined by CIE (1993) as corneal inflammation after overexposure to ultraviolet radiation.

Photoconjunctivitis. Defined by CIE (1993) as a painful conjunctival inflammation that may occur after exposure of the eye to ultraviolet radiation.

Photokeratoconjunctivitis. Inflammation of cornea and conjunctiva after exposure to UV radiation. Wavelengths shorter than 320 nm are most effective in causing this condition. The peak of the action spectrum is approximately at 270 nm. See CIE (1993) for details. *Note:* 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.

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

UV-A 315 to 400 nm
UV-B 280 to 315 nm
UV-C 100 to 280 nm

Ultraviolet germicidal irradiation (UVGI). Use of ultraviolet C-band energy to kill or inactivate microorganisms. UVGI is generated by UV-C lamps that kill or inactivate microorganisms by emitting ultraviolet radiation, predominantly at a wavelength of 253.7 nm.

UV dose. Product of UV irradiance and exposure time on a given microorganism or surface, typically reported in millijoules per square centimetre (mJ/cm^2) or microwatt seconds per square centimetre (μW·s/cm^2).

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

2. UVGI FUNDAMENTALS

Microbial Dose Response

Lamp manufacturers have published design guidance documents for in-duct use (Philips Lighting 1992; Sylvania 1982; Westinghouse 1982). Bahnfleth and Kowalski (2004) and Scheir and Fencl (1996) summarized the literature and discussed in-duct applications. These and other recent papers were based on case studies and previously published performance data. The Air-Conditioning and Refrigeration Technology Institute (ARTI) funded a research project to evaluate UV lamps' capability to inactivate microbial aerosols in ventilation equipment, using established bioaerosol control device performance measures (VanOsdell and Foarde 2002). The data indicated that UV-C systems can be used to inactivate a substantial fraction of environmental bioaerosols in a single pass of air through a duct.

For constant and uniform irradiance, the disinfection effect of UV-C energy on a single microorganism population can be expressed as follows (Phillips Lighting 1992):

$$N_t/N_0 = \exp(-kE_{ff}\Delta t) = \exp(-k \times \text{Dose}) \quad (1)$$

where

N_0 = initial number of microorganisms
N_t = number of microorganisms after any time Δt
N_t/N_0 = fraction of microorganisms surviving
k = microorganism-dependent rate constant, cm^2/(μW·s)
E_{ff} = effective (germicidal) irradiance received by microorganism, μW/cm^2
Dose = $E_{ff} \times \Delta t$, (μW·s)/cm^2

The units shown are common, but others are used as well, including irradiance in W/m^2 and dose in J/m^2 (*note*: 1 J = 1 W·s).

Equation (1) describes an exponential decay in the number of living organisms as a constant level of UV-C exposure continues. The same type of equation is used to describe the effect of disinfectants on a population of microorganisms, with the dose in that case being a concentration-time product. The fractional kill after time t is $(1 - N_t/N_0)$. In an air duct, the use of Equation (1) is complicated by the movement of the target microorganisms in the airstream and the fact that the UV-C irradiance is not of constant intensity within the duct. In addition, the physical parameters of the duct, duct airflow, and UV installation have the potential to affect both the irradiance and the microorganisms' response to it. As is the case with upper-room UV installation design, the design parameters for UV-C in in-duct applications are not simple because of some uncertainty in the data available to analyze them, and because of secondary effects.

A key difference between surface decontamination and airborne inactivation of organisms is exposure time. Residence time in in-duct devices is on the order of seconds or fractions of seconds. In a moving airstream, exposure time is limited by the effective distance in which the average irradiance was calculated; for instance, at 2.54 m/s, 0.3 m of distance takes 0.12 s. Therefore, neutralization methods against an airborne threat must be effective in seconds or fractions of a second, depending on the device's characteristics, and high UV intensity and/or more in-line depth is generally required. Conversely, when irradiating surfaces in an HVAC system, exposure time is typically continuous, so much lower levels of UV intensity are required.

Susceptibility of Microorganisms to UV Energy

Organisms differ in their susceptibility to UV inactivation; Figure 2 shows the general ranking of susceptibility by organism groups. Viruses are a separate case and are not included in Figure 2, because, as a group, their susceptibility to inactivation is even broader than bacteria or fungi. A few examples of familiar pathogenic organisms are included in each group for information (see Table 1). Note that it

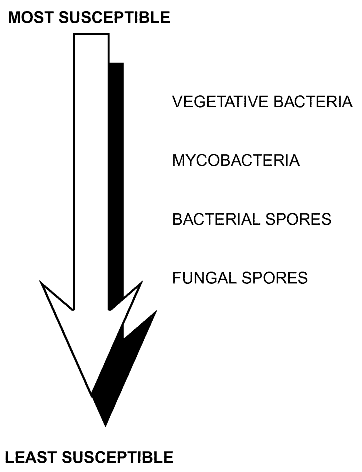

Fig. 2 General Ranking of Susceptibility to UV-C Inactivation of Microorganisms by Group

Table 1 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 spores	*Bacillus anthracis* *Bacillus cereus* *Bacillus subtilis*
Fungal spores	*Aspergillus versicolor* *Penicillium chrysogenum* *Stachybotrys chartarum*

is impossible to list all of the organisms of possible interest in each group. Depending on the application, consult a public health or medical professional, microbiologist, or other individual with knowledge of the threat or organism(s) of concern.

As shown in Figure 2, vegetative bacteria are the most susceptible, followed by the *Mycobacteria*, bacterial spores, and, finally, fungal spores, which are the most resistant. In each group, an individual species may be significantly more resistant or susceptible than others, so take care, using this ranking only as a guideline. Note that spore-forming bacteria and fungi also have vegetative forms, which are markedly more susceptible to inactivation than the spore forms. Using Equation (1), it is clear that larger values of k represent more susceptible microorganisms and smaller values represent less susceptible ones. Units of k are the inverse of the units used for dose.

Using k values to design HVAC duct systems can be challenging. Values of k vary over several orders of magnitude, depending on organism susceptibility, and values reported in the literature for the same microorganism sometimes differ greatly. For example, Luckiesh (1946) reported a k for *Staphylococcus aureus* of 0.9602 m^2/J [0.009602 $cm^2/(\mu W \cdot s)$] and 0.00344 m^2/J for *Aspergillus amstelodami* spores. However, k values for *S. aureus* as small as 0.419 m^2/J were reported by Abshire and Dunton (1981). The wide variation for a single species results from several factors, the most important of which is differences in the conditions under which measurements were conducted (in air, in water, on plates). Especially for many of the vegetative organisms, the amount of protection offered by organic matter, humidity, and components of ambient air can significantly affect their susceptibility to UVGI (VanOsdell and Foarde 2002). Kowalski (2002) has an extensive compilation of published k values, and research to obtain more reliable design values is ongoing. Take care when using published values, and obtain the original papers to evaluate the relevance of the k value of any particular organism to a specific application.

3. LAMPS AND BALLASTS

Types of UV-C Lamps

Although other options exist, the most efficient UV-C lamps are low-pressure mercury discharge lamps. These lamps contain mercury, which vaporizes when the lamp is lighted. The mercury atoms accelerate because of the electrical field in the discharge colliding with the noble gas, and reach an excited stage. The excited mercury atoms emit almost 85% of their energy at 253.7 nm wavelength. Very little energy is emitted in the visible region, so the remaining energy results in various other wavelengths in the UV region (mainly 185 nm). However, most UV-C lamps used for HVAC applications are treated with an interior coating that prevents any vacuum UV (200 nm and below) from being emitted from the lamp, so ozone production is not an issue.

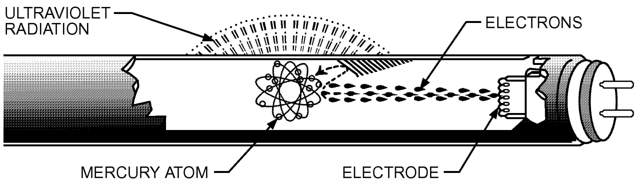

Fig. 3 Typical UVGI Lamp

UV lamps exist in different shapes, which are mostly based on general lighting fluorescent lamps:

- **Cylindrical** lamps may be any length or diameter. Like fluorescent lamps, most UV lamps have electrical connectors at both ends, but single-ended versions also exist. Typical diameters are 38 mm T12, 28 mm T8, 20 mm T6, and 16 mm T5.
- **Biaxial** lamps are essentially two cylindrical lamps that are interconnected at the outer end. These lamps have an electrical connector at only one end.
- **U-tube** lamps are similar to biaxial lamps having the electrical connector at one end. They have a continuously curved bend at the outer end.

UV lamps can be grouped into the following three output types:

- **Standard-output** lamps operate typically at 425 mA.
- **High-output** lamps have hot cathode filaments sized to operate from 800 up to 1200 mA. Gas mixture and pressure are optimized to deliver a much higher UV-C output while maintaining long lamp life, in the same lamp dimensions as standard-output lamps.
- **Amalgam** lamps have hot cathode filaments sized to operate at 1200 mA or higher. The gas mixture, pressure, and sometimes lamp diameter have been optimized for delivering even higher UV output without deteriorating lamp life.

As shown in Figure 3, UV lamps use electrodes between which the electrical discharge runs and are filled with a noble gas such as argon, neon, or a mix thereof. A small amount of mercury is present in the envelope.

The electrodes are very important for the lamp's behavior. There are two major types:

- A **cold-cathode** lamp usually contains a pair of cathodes parallel to one another. The cathodes are not heated in order to excite the electrons. A high voltage potential is needed to ionize the gas in the tube and to cause current flow in an ambient temperature. Cold-cathode lamps offer instant starting, and life is not as affected by on/off cycles. Cold-cathode UV lamps provide less UV-C output than hot-cathode UV lamps, but consume less energy and can potentially last several thousand hours longer, thus requiring less maintenance.
- A **hot cathode** emits electrons through thermo-ionic emission. The electrode consists of an electrical filament coated with a special material that lowers the emission potential. The electrodes are heated by current before starting the discharge and, once started, the discharge current itself can maintain the heat. Hot-cathode lamps typically allow much higher power densities than cold-cathode lamps, and thus generate much more UV-C intensity.

The outer envelope of UV-C lamps is made of special UV-transmitting glass or quartz. Special wires are sealed into this envelope to allow transmission of electrical energy to the electrodes, in a fashion similar to fluorescent lamps.

Two types of glass are used for UV-C lamps. Specialized soft glass is used to produce UV-C lamps that emit 253.7 nm, but the ozone-producing wavelength of 185 nm is filtered out. Quartz glass (hard) can be used to produce UV lamps either with the 253.7 nm output wavelength or with both the 185 and 253.7 nm output wavelengths by changing its transmission properties with internal glass coatings.

To maintain UV output over time, the inside of the glass/quartz tube can also be coated with a special protective layer to slow down the decrease of UV transmission over time.

Mercury can be present in UV lamps as a pure metal or as an amalgam. The amount of mercury is always (slightly) overdosed because some mercury will be chemically bound during the life of the lamp. The actual amount of mercury in the lamp varies, depending on the application, but it can be very small (less than 5 mg). An amalgam is used in lamps having a higher wall temperature because of their higher design working currents. The amalgam keeps the mercury pressure constant over a certain temperature range, providing more stable UV output over that range.

UV-C Lamp Ballasts

All gas discharge lamps, including UV lamps, require a ballast or electronic power supply to operate. The ballast provides a high initial voltage to initiate the discharge, and then rapidly limits the lamp current to safely sustain the discharge. Most lamp manufacturers recommend a particular ballast to operate their lamps, and the American National Standards Institute (ANSI) publishes recommended lamp input specifications for all ANSI type lamps. This information, together with operating conditions such as line voltage, number of switches, etc., allows users to select the proper ballast. Ballasts are designed to operate a unique lamp type; however, typical modern electronic ballasts often adequately operate more than one length, number, or even type of lamp.

It is strongly advised to use the recommended ballast for each lamp type because less than optimum conditions will affect the lamp's starting characteristics, UV-C output, and operating life.

Circuit Type and Operating Mode. Ballasts and electronic power supplies for low-pressure mercury lamps are designed according to the following primary lamp operation modes:

- In **preheat**, lamp electrodes are heated before beginning discharge, and no auxiliary power is applied across the electrodes during operation.
- In **rapid start**, lamp electrodes are heated before and during operation. The ballasts have special secondary windings to provide the proper low voltage to the electrodes during operation. The advantages include smooth starting, longer lamp life, and dimming capabilities.
- **Program start** ballasts incorporate starting steps. The first step applies voltage to electrodes until they are heated to an optimal temperature. The second step applies a lower voltage across the electrodes, thus igniting them with a minimal loss of the filaments' emissive material. This minimal loss ideally equates to a longer lamp life.
- **Instant-start** ballasts do not heat the electrodes before operation. Ballasts for instant-start lamps are designed to provide a relatively high starting voltage (compared to preheat and rapid-start lamps) to initiate discharge across the unheated electrodes. They are not recommended for cold-air applications or if frequent switching is needed.

Preheat mode is more efficient than rapid start, because separate power is not required to continuously heat the electrodes. Electronic ballasts with preheat or program start offer smooth starting, long life, and good switching behavior.

Instant-start operation is more energy efficient than rapid or program start, but output is generally lower and lamp life can be shorter when lamps are frequently switched on and off.

Energy Efficiency. UV lamps convert roughly 30 to 40% of the input power to UV output. Additionally, some of the power supplied into a UV lamp/ballast system produces waste heat energy. There are two primary ways to improve efficiency of a UV lamp/ballast system:

- Use ballasts with a high power factor
- Operate lamp(s) with designed electrical power supplies (recommended)

Newer, more energy-efficient electronic ballasts improve lamp/ballast system efficacy.

Electronic ballasts operate lamps at high frequency (typically more than 20 kHz), allowing the lamps to convert power to UV more efficiently than if operated by electromagnetic ballasts (60 Hz). For example, lamps operated on electronic ballasts can produce over 10% more UV output than if operated on electromagnetic ballasts at the same power input levels.

Power Factor. The ballast power factor is a measure of the actual output for a specific lamp/ballast system relative to the rated output measured with reference ballast under ANSI test conditions (open air at 25°C). It is not a measure of energy efficiency. However, a high power factor ballast does a better job at correcting electrical waveform distortions to deliver current to a lamp in a more energy-efficient manner. For new equipment, high ballast factors are generally the best choice, because fewer lamps and ballasts are needed to reach the system's required UV output.

Audible Noise. Because electronic high-frequency ballasts have smaller magnetic components, they typically have a lower sound rating and should not emit perceptible hum. Most electronic ballasts are A-rated for sound.

EMI/RFI. Because they operate at high frequency, electronic ballasts may produce electromagnetic interference (EMI), which can affect any operating frequency, or radiofrequency interference (RFI), which applies only to radio and television frequencies. This interference could affect the operation of sensitive electrical equipment, such as system controls, televisions, or medical equipment. Good-quality electronic ballasts should incorporate features necessary to maximize protection for the operating environment and to operate well within regulatory limits.

Inrush Current. All electrical devices, including ballasts, have an initial current surge that is greater than their steady-state operating current. National Electrical Manufacturers Association (NEMA) *Standard* 410 covers worst-case ballast inrush currents. All circuit breakers and light switches are designed for inrush currents. The electrical system should be designed with this issue in mind.

Total Harmonic Distortion (THD). Harmonic distortion occurs when the wave-shape of current or voltage varies from a pure sine wave. Except for a simple resistor, all electronic devices, including electromagnetic and electronic ballasts, contribute to power line distortion. For ballasts, THD is generally considered the percent of harmonic current the ballast adds to the power distribution system. ANSI *Standard* C82.11 for electronic ballasts specifies a maximum THD of 32%. However, most electric utilities now require that the THD of electronic ballasts be 20% or less.

Dimming. Unlike incandescent lamps, a UV lamp can only be dimmed when its electrode temperature is maintained while the lamp arc current or voltage is reduced.

Electronic dimming ballasts alter the output power to the lamps in the ballast itself, driven by a low-voltage signal into the driver circuit. This allows control of one or more ballasts independent of the electrical distribution system. With dimming electronic ballast systems, a low-voltage control network can be used to group ballasts into arbitrarily sized control zones. Dimming range differs greatly; most electronic dimming ballasts can vary output levels between 100% and about 10% of full output, but ballasts are also available that operate lamps down to 1% of full output.

Germicidal Lamp Cooling and Heating Effects

Output of UV lamps is dependent on mercury vapor pressure within the lamp envelope. The mercury vapor pressure is controlled by the temperature of the cold spot (the coldest portion of the UV lamp during lamp operation), as shown in Figure 4. If the mercury vapor pressure is low, UV output will be low because there are not enough mercury atoms to generate full UV radiation. Too high a mercury vapor pressure can also decrease UV output, because the excess evaporated mercury absorbs ultraviolet rays generated in the UV lamp.

In low-pressure mercury lamps, mercury vapor pressure reaches its optimal level in still air at 25°C. Depending on lamp type, the cold-spot temperature must be between 38 and 50°C to reach maximum UV output. In moving air, the cold-spot temperature of standard lamps may be too low to reach the required UV output (Figure 5). Special windchill-corrected lamps can be designed to make the lamps function more optimally in cold moving air.

By introducing mercury into the lamp in the form of amalgams, the cold-spot temperature can be increased to between 70 and 120°C, making it possible to reach optimum UV output at higher temperatures. Amalgams provide a broadened peak in UV output versus temperature, so that near-optimum UV output is obtained over an extended range of ambient temperatures.

UV-C Lamp Aging

Output of UV-C lamps decreases over time. UV-C lamps are rated in effective hours of UV-C emission, and not in end of electrical life hours. Many UV-C lamps are designed to emit intensity levels at the end of their useful life that are 50 to 85% or more of that measured at initial operation (after 100 h burn-in time), although current models continue to emit blue visible light long after they have passed their useful life. Lamp manufacturers' specification data can verify depreciation over useful life. UV-C systems should be designed for the output at the end of effective life.

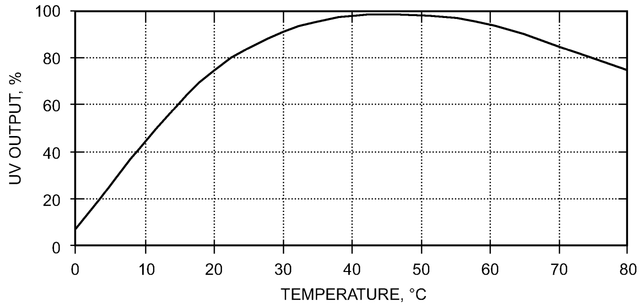

Fig. 4 Example of Lamp Output as Function of Cold-Spot Temperature

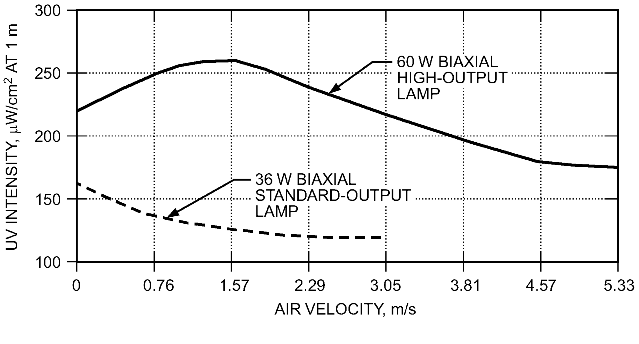

Fig. 5 Windchill Effect on UV-C Lamp Efficiency

UV-C lamps have a wide range of useful life hours, depending on the type of glass envelope used, any protective internal glass wall coatings, filament current load design, gas mixture, gas pressure, and ballast type.

UV-C Lamp Irradiance

UV-C lamp intensity is measured in μW/cm², and manufacturers typically obtain their lamp intensity measurements by taking the UV-C intensity reading 1 m from the center of a UV lamp, in an open-air ambient of approximately 24°C and with approximately zero air movement. ASHRAE *Standards* 185.1-2015 and 185.2-2014 address test standard protocols for measuring UV-C lamp system outputs and their ability to inactivate airborne and surface microorganisms, respectively.

The irradiance E on a small surface at point P on a distance a from a linear UV-C lamp length AB = L can be calculated using Equation (2) if the UV output of the lamp is represented by ϕ (Figure 6):

$$E = \frac{\phi}{2\pi^2 La}(2\alpha + \sin 2\alpha) \qquad (2)$$

At shorter distances ($a < 0.5L$), the irradiance is inversely proportional to the distance of the measurement point from the lamp, as can be seen from the following simplified equation.

$$E = \frac{\phi}{2\pi La} \qquad (3)$$

UV-C Photodegradation of Materials

The UV-C energy used in HVAC applications can be very detrimental to organic materials (ACGIH 2015; Bolton 2001; Kauffman 2011). As such, if the UV is not applied properly and vulnerable materials are not shielded or substituted, substantial degradation can occur (NEHC 1992). Material degradation can result in decreased filtration efficiency, defective seals, and damaged system components, causing a possible loss in system performance and/or potential safety concerns.

In an HVAC system, the extent of material degradation caused by UV-C energy varies greatly with the material, UV intensity, length of exposure, and design of the component. UV-C intensity in a system can be as high as 10 000 μW/cm² for airstream disinfection, or about 50 to 100 μW/cm² (typical) for cooling coil maintenance.

For many HVAC components, such as certain filter media and insulation or gasket foams, degradation can be rapid and severe, destroying the material (Kauffman 2011). Of particular concern are many types of synthetic media filters, which may degrade rapidly; other media may be better suited for HVAC systems using UV-C disinfection. However, many filters of a woven or "laid up" glass media (e.g., HEPA filters) maintain integrity with intensive UV-C exposure. Lofted or unwoven glass filters that depend on a high percentage of binders for strength may not do as well with UV exposure, because some of the binder material can be degraded. Filter degradation could vary based on filter design, material composition, and level of UV-C exposure. For other materials and components, with substantial cross section and fabricated from solid polymers,

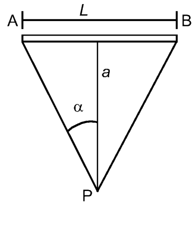

Fig. 6 Diagram of Irradiance Calculation

Table 2 Summary of UV-C Resistance Ratings of Tested Materials

Polymers		
Rating B	**Rating C**	**Rating D**
Polyvinyl formal (4)	Polyimide (30)	Acrylic (80)
Nylon black (10)	LDPE (30)	PET (90)
Natural nylon (10)	ABS (30)	PBT (90)
Perfluoroethylene (20)	Cast epoxy (40)	Polypropylene (200)
	Polyvinyl chloride (40)	HDPE (400)
	Polycarbonate (60)	Polyacetal (700)
	Phenolic resin	
Elastomers/Sealants		
Rating B	**Rating C**	**Rating D**
Copper/petroleum RTV		Acetic acid RTV
Latex rubber		
Buna-N O-ring		
EPDM O-ring		
Silicone O-ring		
Filter Media and Support Materials		
Rating B	**Rating C**	**Rating D**
Low-lint wipes (10)[b]	Printer paper (100)[b]	Polyester[a] (400)
Hot-melt adhesive (70)[b]	Polyurethane strips (100)[b]	Cardboard (1000)[b]
	Industrial HEPA (100-200)[b]	Lofted glass fiber[a] (7000)[b]
	HEPA consumer (200)[b]	
	Electret (300)[b]	
Miscellaneous Materials		
Rating B	**Rating C**	**Rating D**
Elastomeric isolator (30)	Polyurethane door gasket (20)	Glass fiber insulation[a] (90)
Elastomeric V-belt (70)	Mastic duct sealant (400)	Neoprene door gasket[a] (100)
		Foam pipe insulation[a] (300)
		Polystyrene foam[a] (400)

Source: Kauffman (2011). [a]Structural damage: crumbled, lost fibers, etc. [b]Slope from 10 000 μW/cm^2 test

Notes:
1. Only aluminum tape (inorganic) received an A rating.
2. Numbers in parentheses refer to rate of UV degradation; lower numbers indicate greater UV resistance. Parenthetical ratings are arbitrary and for relative linear comparison only.

degradation can be negligible (Kauffman 2011, 2012; Kauffman and Wolf 2012, 2013). Inorganic materials such as glass, glass fibers, and metal are not affected by UV-C exposure.

To qualify the ability of various materials to withstand UV-C energy, ASHRAE sponsored research project RP-1509, which tested many common polymeric components used in HVAC systems (Kauffman 2011). The detailed data in the report can be used to estimate degradation of an item at different UV intensity levels and exposure times; Table 2 gives an overview that can be used to determine what materials to avoid or shield in a system. A full discussion of this study is beyond the scope of this chapter. For more precise estimates of component life, it is highly recommended that the system designer refer to the final published results. Because RP-1509 is not fully conclusive, accelerated testing should be performed for some critical components (Kauffman 2011, 2012; Kauffman and Wolf 2012, 2013).

Rates of photodegradation varied greatly among the materials tested during this project. As a general rule, solid materials performed better than porous/fibrous materials because of the minimal surface penetration by UV-C radiation. Based on the relative degradation, the materials were ranked with respect to the UV-C resistance as follows:

- A: No effect (inorganic materials only; all organic materials exhibit some degradation)
- B: Minor effect (mainly cosmetic changes, not likely to affect materials ability to perform its duty)
- C: Moderate effect (some cracking/pitting suggesting protection/shielding should be considered)
- D: Severe effect (structural damage, not recommended)

The only material tested in the study that received an A rating was aluminum tape (inorganic). The results for all other materials tested are shown in Table 2.

Note that parenthetical ratings in Table 2 are arbitrary and are intended for comparing the UV-C resistances of the different materials (e.g., in the elastomer/sealant section of the table, copper-cured RTV is more resistant to UV-C than acetic-acid-cured RTV) on a linear scale. The polymers were rated based on surface crater formation (loss of mass), whereas the other materials were based on mass loss and/or changes in flexibility.

The usefulness of the photodegradation ratings in Table 2 have to be weighed with many factors, such as level of irradiance, thickness of component, and function of the component. For example, although a drip pan made from LDPE would perform much better than one made from PBT or HDPE according to the table, the difference in performance would become minimal below 1000 μW/cm^2. Also, the pan's thickness may require several years before any fissures or leaks would occur. On the other hand, electrical wiring with thin (2 mil) polyvinyl formal insulation would inhibit an electrical short (assuming a 50% loss of insulation) for over eight years when exposed to 11 000 μW/cm^2, whereas wire insulated with polyimide may short in less than one year.

Other processing factors, such as material porosity, fillers, plasticizers, extrusion temperature, etc., also affect performance of the selected material (e.g., LDPE performed better under UV-C than HPDE, and polyvinyl chloride samples with different fillers and obtained from two different sources degraded quite differently) (Kauffman 2011). Materials can be engineered to withstand UV-C, for example, by adding UV-C absorbers such as benzophenones for polyvinyl chloride or benzotriazoles and hydroxyphenyltriazines for polycarbonate.

Although UV-C photodegradation is of concern, with the selection of the proper material or metallic shielding of other 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 1.5 m of the UV lamp.

4. MAINTENANCE

Lamp Replacement

UV lamps should be replaced at the end of their useful life, based on recommendations of the equipment manufacturer. It may be prudent to simply change lamps annually (8760 h when lamps are run continuously) to ensure that adequate UV energy is supplied. Lamps can operate long after their useful life, but at greatly reduced performance. The typical useful life of UV-C lamps is 9000 h of continuous 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 Disposal

UV lamps should be treated the same as other mercury-containing devices, such as fluorescent bulbs, according to local regulations. Most lamps must be treated as hazardous waste and cannot be discarded with regular waste. Low-mercury bulbs often can be discarded as regular waste; however, some state and local jurisdictions classify these lamps as hazardous waste. The U.S. EPA's universal waste regulations allow users to treat mercury lamps as regular waste for the purpose of transporting to a recycling facility (EPA 2011). This simplified process was developed to promote recycling. The National Electrical Manufacturers Association (NEMA) maintains a list of companies claiming to recycle or handle used mercury lamps at www.lamprecycle.org.

Visual Inspection

Maintenance personnel should routinely perform periodic visual inspection of the UV lamp assembly. Typically, a viewing port or an access door window is sufficient. Any burned-out or failing lamps should be replaced immediately.

Depending on the application and environment, a maintenance plan may need to include direct physical inspection of the fixture. If the lamp has become dirty, it should be cleaned with a lint-free cloth and commercial glass cleaner or alcohol.

Future UV-C systems may include a feedback component to alert maintenance personnel to UV-C lamp failure or output decline.

5. SAFETY

Hazards of Ultraviolet Radiation to Humans

UV-C is a low-penetrating form of UV compared to UV-A or UV-B. Measurements of human tissue show that 4 to 7% of UV-C (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 cornea (outer dead layer of human skin), thus minimizing the amount of UV-C transmitted through the epidermis (Bruls 1984).

Although UV is more energetic than the visible portion of the electromagnetic spectrum, UV is invisible to humans. Therefore, exposure to ultraviolet energy may result in ocular damage, which may initially go unnoticed.

Ocular damage generally begins with **photokeratitis** (inflammation of the cornea), but can also result in **keratoconjunctivitis** [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 within 24 to 48 h.

Cutaneous damage consists of erythema, a reddening of the skin. It is like a sunburn with no tanning. The maximum effect of erythema occurs at a wavelength of 296.7 nm in the UV-B band. UV-C radiation at a wavelength of 253.7 nm is less effective, but is still a skin hazard.

The International Commission on Illumination (CIE) provides a thorough review of UV-C **photocarcinogenesis** risks from germicidal lamps (CIE 2010).

Acute **overexposure** to UV-C band radiation is incapacitating, but generally regresses after several days, leaving no permanent damage.

Sources of UV Exposure

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

UV-C energy can reflect from most polished 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-C reflectance. The fact that a blue glow can be observed on the 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. The lack of reflected blue light does not necessarily indicate the absence of UV energy.

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

Table 3 lists some permissible exposure times for different levels of UV-C irradiance. Exposures exceeding CDC/NIOSH REL levels require use of personal protective equipment (PPE), which consists of eyewear and clothing known to be nontransparent to UV-C penetration and which covers exposed eyes and skin.

UV inspection, maintenance, and repair workers typically do not remain in one location during the course of their workday, and therefore are not exposed to UV irradiance levels for 8 h. Threshold Limit Value® (TLV®) consideration should be based on occupancy use of spaces treated by UV-C systems (ACGIH 2015).

Some indoor plants do not tolerate prolonged UV-C exposure and should not be hung in the upper room.

At 253.7 nm, the CDC/NIOSH REL is 6 mJ/cm^2 (6000 μJ/cm^2) for a daily 8 h work shift. ACGIH's (2015) TLV for UV radiation is identical to the REL for this spectral region. Permissible exposure times (PET) can be calculated for various irradiance levels using the following equation:

$$\text{PET, s} = \frac{\text{REL of 6000 } \mu\text{J/cm}^2 \text{ at 254 nm}}{\text{Measured irradiance level at 254 nm in } \mu\text{W/cm}^2} \quad (4)$$

Table 3 Permissible Exposure Times for Given Effective Irradiance Levels of UV-C Energy at 253.7 nm

Permissible Exposure Time*	Effective Irradiance, μW/cm²
24 h	0.07
18 h	0.09
12 h	0.14
10 h	0.17
8 h	0.2
4 h	0.4
2 h	0.8
1 h	1.7
30 min	3.3
15 min	6.7
10 min	10
5 min	20
1 min	100
30 s	200
15 s	400
5 s	1200
1 s	6000

UV Radiation Measurements for Upper Air Applications

UV levels can be measured with a UV radiometer directly facing the device at eye height at various locations in a room or occupied space, and must be taken in the same location each time. If the readings indicate a dosage exceeding 6 mJ/cm^2, the UV systems must be deactivated until adjustments can be made or the manufacturer can be contacted. UV radiation measurements should be taken

- At initial installation
- Whenever new lamps are installed (newer lamp designs may have increased irradiance)
- Whenever modifications are made to the UVGI system or room (e.g., adjusting fixture height or location or position of louvers, adding UV-absorbing or -reflecting materials, changing room dimensions or modular partition height)

Safety Design Guidance

In-duct systems should be fully enclosed to prevent leakage of UV radiation to unprotected persons or materials outside of the HVAC equipment.

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 have warning labels in appropriate languages. Labels should be on the outside of each panel or door, in a prominent location visible to people accessing the system.

Lamp chambers should also have electrical disconnect devices. Positive disconnection devices are preferred over switches. 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. Devices should be wired in series so that opening any access deenergizes the system. On/off devices for UV lamps must not be located in the same location as general room lighting; instead, they must be in a location that only authorized persons can access, and should be locked to ensure that they are not accidentally turned on or off.

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

Upper-air 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-air UV fixtures to alert personnel of 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-air UV-C
  Caution: Ultraviolet energy. Switch off lamps before entering upper room.
- General warning posted near UV-C lamps
  Caution: Ultraviolet energy. Protect eyes and skin.
- Warning posted on the door of air handlers where UV-C lamps are present in ductwork
  Caution: Ultraviolet energy in duct. Do not override the safety device or otherwise activate lamps with door open.

UV systems may be subject to the requirements of UL *Standard* 1995; the planned revision of this standard includes requirements for UV applications in HVAC systems and ducts.

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 should include

- UV exposure hazards
- Electrical safety
- Lock-out/tag-out
- Health hazards of mercury
- Rotating machinery
- Slippery condensate pans
- Sharp unfinished edges
- Confined-space entry (if applicable)
- 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 eyewear, including prescription glasses, may be sufficient to protect eyes from UV, but not all offer complete coverage (energy could still reach the eyes from the sides or reflections from inside the glasses); standard-issue, full wraparound protective goggles may be the best alternative.

If individual lamp operating condition must be observed, this should preferably be done using the viewport window(s).

Access to lamps should only be allowed when lamps are deenergized. The lamps should be turned off before air-handling unit (AHU) or fan shutdown to allow the lamps 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, open the lamp chamber and allow it to ventilate for several minutes if ozone lamps are used. 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 will 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., to test for output reduction caused by air cooling). Tests of this nature should be instrumented and monitored from outside the equipment.

During maintenance, renovation, or repair work in rooms where upper-air UV systems are present, all UVGI systems must be deactivated before personnel enter the upper part of the room.

Lamp Breakage

If a lamp breaks, all workers must exit the HVAC equipment. 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 a period of 15 minutes, 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. Carefully set the broken lamp down, then exit the equipment. 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 lamp 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.

6. UNIT CONVERSIONS

Just as it is customary to express the size of aerosols in micrometres and electrical equipment's power consumption in watts, regardless of the prevailing unit system, it is also customary to express total lamp UV output, UV fluence, and UV dose using SI units.

Multiply I-P	By	To Obtain SI
Btu/ft^2 (International Table)	1135.65	mJ/cm^2
$Btu/h \cdot ft^2$	315.46	$\mu W/cm^2$
To Obtain I-P	**By**	**Divide SI**

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