[Related Commercial Resources]

CHAPTER 16

ULTRAVIOLET LAMP SYSTEMS

USE of ultraviolet (UV) lamps and lamp systems to disinfect room air and air streams 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 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:

- UVA (long-wave; 400 to 315 nm): the most abundant in sunlight, responsible for skin tanning and wrinkles
- UVB (medium-wave; 315 to 280 nm): primarily responsible for skin reddening and skin cancer
- UVC (short-wave; 280 to 200 nm): the most effective wavelengths for germicidal control
- Far or vacuum UV (200 to 30 nm)

UVC energy disrupts the DNA of a wide range of microorganisms, rendering them harmless (Brickner 2003; CIE 2003). Figure 1 shows the DNA response to UV energy. Most, if not all commercial germicidal lamps are low-pressure mercury lamps that emit UV energy at 253.7 nm, very close to the optimal wavelength.

Ultraviolet germicidal irradiation (UVGI) has been used in air ducts for some time, and its use is becoming increasingly frequent as concern about indoor air quality increases. UVGI is being 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 2003; CDC 2002, 2005; General Services Administration 2003).

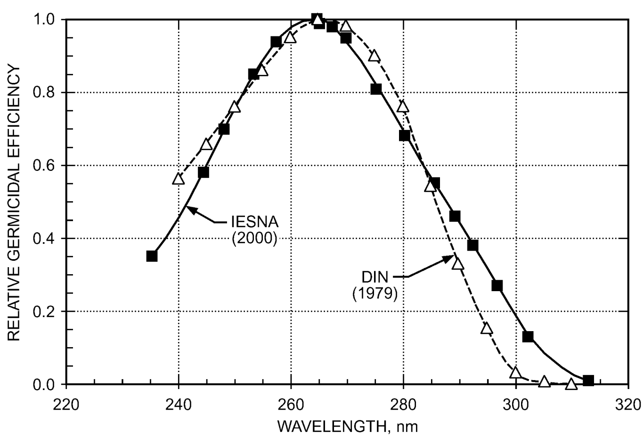


Fig. 1 Relative Germicidal Efficiency

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

This chapter includes a review of the fundamentals of UVC germicidal energy's impact on microorganisms; how UVC lamps generate germicidal radiant energy; common approaches to the application of UVGI systems for upper-air room, in-duct, and surface cleansing; and a review of human safety and maintenance issues.

TERMINOLOGY

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

Droplet nuclei. Microscopic particles produced when a 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.

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, 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.

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 (μW/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 (λ ≈ 1 nm) and radio waves (λ ≈ 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

UVA	315 to 400 nm
UVB	280 to 315 nm
UVC	100 to 280 nm

Ultraviolet germicidal irradiation (UVGI). Use of ultraviolet radiation to kill or inactivate microorganisms. UVGI is generated by germicidal lamps that kill or inactivate microorganisms by emitting ultraviolet germicidal 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 centimeter (mJ/cm^2).

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

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' availability to inactivate microbial aerosols in ventilation equipment, using established bioaerosol control device performance measures (VanOsdell and Foarde 2002). The data indicated that UVC systems can be used to inactivate a substantial fraction of environmental bioaerosols in a single pass.

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

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

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.

Equation (1) describes an exponential decay in the number of living organisms as a constant level of UVGI 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 UVGI irradiance is not constant 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 UVGI 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 500 fpm, 1 ft 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 is generally required. Conversely, when irradiating surfaces in an HVAC system, exposure time is often continuous, so much lower levels of UV intensity may be 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. Note that it is impossible to list all of the organisms of interest in each group (see Table 1). 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.

As shown in Figure 2, the vegetative bacteria are the most susceptible, followed by the *Mycobacteria*, bacterial spores, and, finally, fungal spores, which are the most resistant. Within each group, an individual species may be significantly more resistant or susceptible than others, so care should be taken, using this ranking only as a guideline. Note that spore-forming bacteria and fungi also

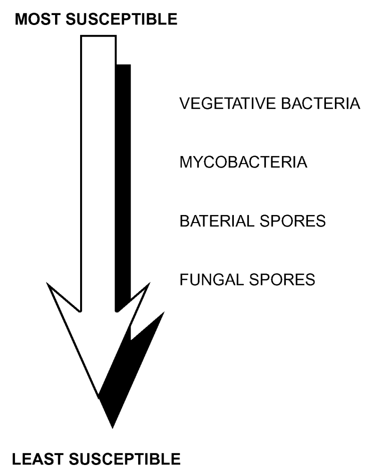


Fig. 2 General Ranking of Susceptibility to UVC Inactivation of Microorganisms by Group

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*

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 is the result of a number of 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.

LAMPS AND BALLASTS

Types of Germicidal Lamps

UV lamps are based on a low-pressure mercury discharge. 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. The remaining energy is emitted at various wavelengths in the UV region (mainly 185 nm); very little is emitted in the visible region.

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 1.5 in. T12, 1.1 in. T8, 0.79 in. T6, and 0.63 in. 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.

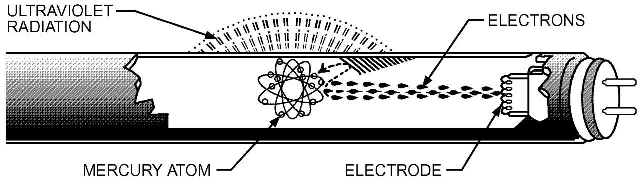


Fig. 3 Typical UVGI Lamp

- **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 UVC 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 an even higher UV 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. The outer envelope is made out of a UV transmitting material such as quartz or a special soda barium glass (sometimes called soft glass). A small amount of mercury is present in the envelope.

The electrodes are very important for the lamp 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 affected by on/off cycles. Cold-cathode UV lamps provide less UVGI output than hot-cathode UV lamps, but consume less energy and last several thousand hours longer, thus requiring less costly maintenance.
- A **hot cathode** emits electrons through thermo-ionic emission. The electrode consists of an electrical filament coated with a special material (emittor) that lowers the emission potential. The electrodes are heated by current before starting the discharge and, once started, by the discharge current itself. Hot-cathode lamps typically allow much higher power densities than cold-cathode lamps, and thus generate much more UVGI intensity.

The outer envelope of UV lamps is made of UV-transmitting soft glass or quartz. Special wires are vacuum sealed into this envelope to allow transmission of electrical energy to the electrodes.

Soft glass can be used to produce UV lamps that emit 253.7 nm, but it is not suitable for producing the ozone wavelength of 185 nm. Fused quartz silica can be used to produce UV lamps with either only 253.7 nm output or with 185 nm/253.7 nm output by changing its transmission properties.

To maintain UV output over time, the inside of the glass/quartz tube can be coated with a special 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. Depending on the application, the amount of mercury in the lamp can be 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.

Germicidal 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 one or more ballasts 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 proper ballast. Ballasts are designed to optimally operate a unique lamp type; however, modern electronic ballasts often adequately operate more than one 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, light output, and operating life.

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

- In **preheat**, lamp electrodes are heated before beginning discharge. No auxiliary power is applied across the electrodes during operation.
- In **rapid start**, lamp electrodes are heated before and during operation. The ballast transformers have two special secondary windings to provide the proper low voltage to the electrodes. The advantages include smooth starting, long life, and dimming capabilities.
- **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 if frequent switching is needed.

Preheat mode is more efficient than rapid start, because separate power is not required to continuously heat the electrodes. If operated with glow starters, lamps tend to flicker during starting. Electronic ballasts with preheat offer smooth starting, long life, and good switching behavior.

Instant-start operation is more efficient than rapid start, but lamp life is shorter, especially when lamps are frequently switched on and off.

Energy Efficiency. UV lamps are very efficient at converting input power to UV output; nevertheless, much of the power supplied into a UV lamp-ballast system produces waste heat energy. There are three primary ways to improve efficiency of a UV lamp-ballast system:

- Reduce ballast losses
- Operate lamp(s) at a high frequency
- Reduce losses attributable to lamp electrodes

Newer, more energy-efficient ballasts, both magnetic and electronic, use one or more of these techniques to improve lamp-ballast system efficacy, measured in lumens per watt.

Losses in magnetic ballasts have been reduced by using higher-grade magnetic components. Some rapid-start magnetic ballasts improve efficacy by removing power to the lamp electrodes after starting. Using a single ballast to drive three or four lamps, instead of only one or two, may also reduce ballast losses.

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. For example, lamps operated on electronic ballasts can produce over 10% more UV than if operated on electromagnetic ballasts at the same power levels.

Ballast Factor. The ballast 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 77°F). Ballast factor is not a measure of energy efficiency. Although a lower ballast lumen factor reduces lamp lumen output, it also consumes proportionally less input power. A low ballast lumen factor may drastically reduce lamp life, because the lamp electrodes run too cold.

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. Iron-cored electromagnetic ballasts operating at 60 Hz generate audible noise, because of electromagnetic action in the core and coil assembly of the ballast. Noise can increase at high temperatures, and it can be amplified by some luminaries' designs. The best ballasts use high-quality materials and construction to reduce noise. Noise is rated A, B, C, or D, in decreasing order of preference: an A-rated ballast hums softly; a D-rated ballast makes a loud buzz. Virtually all energy-efficient magnetic ballasts for G36T5L and G30T8 lamps are A-rated, with a few exceptions (e.g., low-temperature ballasts).

Because electronic high-frequency ballasts have smaller magnetic components, they typically have a lower sound rating and should not emit perceptible hum. All 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. The ANSI standard 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, UV lamps cannot be properly dimmed with a simple wall box device. For a UV lamp to be dimmed over a full range without reducing lamp life, its electrode temperature must be maintained while the lamp arc current is reduced.

Dimming ballasts are available in both magnetic and electronic versions. **Magnetic dimming ballasts** require control gear containing expensive, high-power switching devices that condition the input power delivered to the ballasts. This is economically viable only when controlling large numbers of ballasts on the same branch circuit.

Electronic dimming ballasts alter the output power to the lamps within 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 critically 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 too low, UV output is low because there are not enough mercury atoms to generate UV radiation. Too high a mercury vapor pressure also decreases UV output, because the excess evaporated mercury absorbs ultraviolet rays generated in the UVGI lamp.

In low-pressure mercury lamps, mercury vapor pressure reaches its optimal level in still air at 77°F. Depending on lamp type, the cold-spot temperature must be between 103 and 122°F to reach maximum UV output. In moving air, the cold-spot temperature of standard lamps is too low to reach the necessary UV output (Figure 5). Special windchill-corrected lamps are designed to make the lamps function optimally in moving air.

By introducing mercury into the lamp in the form of amalgams, the cold-spot temperature can be increased to between 158 and 248°F, making it possible to reach optimum UV output at higher temperatures. Amalgams reduce mercury vapor pressure relative to that of pure mercury at any given temperature, and also provide a broadened peak in UV output versus temperature (see curve), so that near-optimum light output is obtained over an extended range of ambient temperatures.

Germicidal Lamp Aging

Output of UV lamps decreases over time. UV lamps are rated in effective hours of UV emission, and not in end of electrical life hours. Many UV 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), although current models continue to emit blue light long after they have passed their useful life. Lamp manufacturers' specification data can verify depreciation over useful life. UVGI systems should be designed for the output at the end of effective life.

Cold-cathode UV lamps can have useful life rating of approximately 20,000 h. Hot-cathode UV 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 pressure, and gas mixture. Consequently, hot-cathode UV lamps can have useful lives ranging from 6000 to 13,000 h.

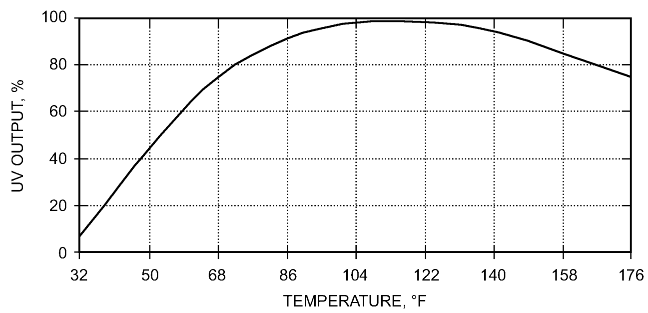


Fig. 4 Example of Lamp Efficiency as Function of Cold-Spot Temperature

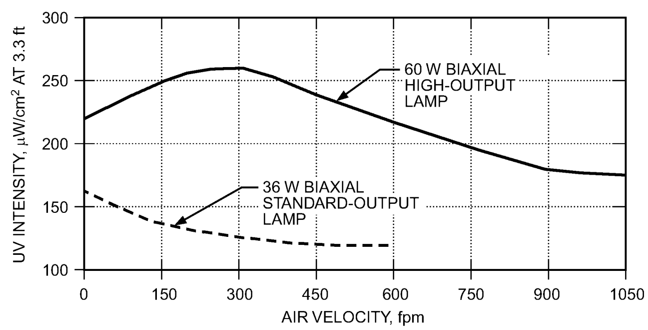


Fig. 5 Windchill Effect on UVC Lamp Efficiency

UVGI Lamp Irradiance

UVGI lamp intensity is measured in $\mu W/cm^2$. Often, manufacturers obtain their lamp intensity measurements by taking a UV intensity reading 3.3 ft from the center of a UVGI lamp, in an open-air ambient of approximately 75°F and with approximately zero air velocity. Test standard protocols for measuring UVC lamps' ability to inactivate airborne and surface microorganisms are currently being developed by ASHRAE Standard Project Committee SPC 185.

The irradiance E on a small surface in point P on a distance a from a linear UV lamp length AB = L can be calculated with the following equation if the UV output of the lamp is represented by ϕ (Figure 6):

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

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.

$$E = \frac{\phi}{2\pi La} \tag{3}$$

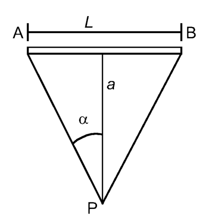
APPLICATION

Ultraviolet Fixture Configurations

Upper Air Fixtures. Wall-mounted fixtures with louvers are designed to keep ultraviolet rays above eye and head level. Specially designed louvers keep the rays from bouncing off the ceiling and in a vertical path above 7 ft. These fixtures reduce airborne microorganisms as normal air convection moves them into the path of the ultraviolet rays, where they are inactivated. Some fixtures also use small fans to help circulate the air by the UV fixture.

Ceiling-suspended fixtures are designed in the same way as wall mounted fixtures, incorporating louvers and/or UV traps to keep the rays out of eye and head level.

In-Duct Units. In-duct UVGI systems are designed to mount inside an air-conditioning duct; the UV energy is confined to the inside of the duct. They are normally installed with a safety interlock,



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

Fig. 6 Diagram of Irradiance Calculation

so if the fixture is removed from the duct or an access door is opened, the lamps turn off to avoid accidental human exposure to UV energy.

In-duct UVGI systems can be used to irradiate cooling coils, drain pans, and other HVAC components, or to disinfect moving air.

In-Duct Airstream Disinfection

In-duct UVGI systems disinfect an airstream in a building or room ventilation system. These systems are designed to treat the airflow and use available space within the duct. In-duct systems are generally engineered to achieve a required level of air disinfection and are often unique to each installation.

Numerous variables must be factored in to properly size and apply a UVGI system for airstream disinfection, including the following:

- Duct height and width
- Duct length where airstream is exposed to UV
- Air velocity
- Air temperature
- Lamp cooling effect of temperature and air velocity
- Lamp fouling (decreases the UV delivered)
- Biocontaminants and their *k* values (sensitivity to UV)
- Disinfection performance required
- Lamp age
- Type of power supply driving the UV lamp
- Reflectivity of duct material or duct lining
- Location of lamps with respect to duct
- Humidity

Outside makeup air cannot be treated if it is brought in downstream from where the UV fixtures are mounted, unless the makeup air is treated separately. Mounting the UVGI fixtures in the supply plenum ensures that both return and makeup air are treated.

UV lamps may be installed in different orientations, including the following:

- Perpendicular to airflow
- Parallel to airflow, with lamp(s) radiating outwardly
- Parallel to airflow, with lamp(s) radiating inwardly

In any UV installation, performance can be improved by increasing the UVC reflectivity of the duct walls. Note that air ducts may have different reflective properties, but typical galvanized duct material has a UVC reflectivity of about 57%. Aluminum and other more UVC-reflective materials may be used as lines to improve reflectivity. Most manufacturers have this information, and it should be included in the dosage calculations. Table 2 provides typical approximations, but actual material should be tested.

Table 2 Material Reflectivity

Material	Reflectance, %
Aluminum, etched	88
Aluminum foil	73
Aluminum paint	40 to 75
Chromium	45
Galvanized	57
Glass	4
Magnesium oxide	75
Nickel	38
Silver	22
Stainless steel	20 to 30
Tin-plated steel	28
Typical duct liner	0 to 1
White cotton	30
White oil paints	5 to 10
White paper	25
White porcelain enamel	5
White wall plaster	40 to 60
White water paint	10 to 35

The number and location of UVGI fixtures are dictated by the average percentage of reduction desired of the targeted biocontaminants in the duct, taking into account all of the variables mentioned previously.

Maintenance procedures should be as specified by the UVGI equipment manufacturer.

Air Handler Component Surface Disinfection

Applications of UV include uses in hospitals, schools, office buildings, food, pharmaceutical and commercial buildings, and even homes (Bernstein et al. 2006; Blatt et al. 2006). Since 2000, the General Services Administration (GSA) has required UV to be applied to the air-conditioning coils and drain pans of all HVAC systems in every GSA-funded new construction project (Department of General Services; GSA 2003).

As HVAC equipment ages, its performance can degrade, and so may the quality of air it delivers to occupied spaces (Kowalski 2006). Cooling coils can act as filters to collect and retain a substantial amount of particulates, including microbes (Siegel et al. 2002). These materials are quite small, so this occurs even in a system with reasonable or good filtration. Between 30 and 100% rh, damp coil and drain pan conditions are excellent forums for the growth of bacteria and mold (Levetin et al. 2001). Coil fouling also increases coil pressure drop and reduces airflow, reducing heat transfer from coil fins to lessen the amount of work a system can perform (Montgomery and Baker 2006) and reducing indoor environmental quality (IEQ). It can contribute to sick building syndrome and building-related illnesses ranging from mild irritations to the spread of infectious agents (Menzies et al. 2003). The decaying accumulation is often a source of odor, as well (Kowalski 2006).

Periodically cleaning the coils and drain pan is recommended by system manufacturers, though it is not always practical. Traditional coil cleaning, such as steam cleaning and chemical pressure washing, can restore system performance, improve air quality, and reduce energy consumption (Montgomery and Baker 2006). However, chemical and mechanical cleaning can be dangerous, costly, and difficult. Chemicals can contribute to air quality problems, and mechanical cleaning can reduce coil efficiency and life. In addition, system performance begins to degrade again shortly after cleaning.

UVGI can be readily applied to HVAC systems to help maintain system cleanliness (Blatt et al. 2006). It is used to complement system maintenance by keeping coils, drain pans, and other surfaces clean and free of microbial contamination. Stationary surfaces receive UVC doses many orders of magnitude higher than microbes in moving air do, making it relatively easy, using lower levels of UV, to maintain heat exchange efficiency, design airflow, and to improve indoor air quality by reducing the growth of bacteria and mold on system components.

UVGI reduces microbial levels on HVAC surfaces and often in the air (RLW Analytics 2006). Coil pressure drop is reduced and, therefore, airflow is restored (Witham 2005). Because heat transfer also is restored, this combination can result in energy savings (Levetin et al. 2001), which can be significant, with payback of possibly less than two years (Montgomery and Baker 2006). In addition, the associated improvements in air quality may reduce respiratory distress symptoms and thus improve attendance and work performance in occupied spaces (Bernstein et al. 2006; Menzies et al. 2003).

Installation. Coils should be cleaned initially to reduce biomass and to accelerate systemwide cleaning and energy savings. UV lamps should be mounted near cooling coils and spaced to allow even distribution of energy over the surface to be disinfected. Qualified UV equipment manufacturers or consultants can assist in system design.

UVGI fixtures for HVAC equipment must be designed to withstand moisture and condensate (from the coil or caused by reduced operating temperatures) and to operate properly over the full range of system operating temperatures. Care must be taken at the installation

Table 3 Advantages and Disadvantages of UVC Fixture Location Relative to Coil

Location	Advantages	Disadvantages
Downstream	More space to install fixtures. Allows fixtures to better irradiate surface where condensation is highest. Allows fixtures to irradiate generally most contaminated part of coil and drain pan.	Lamp and fixture must be rated for damp location. Lamp cooling effects may reduce UV output, or require windchill correction or more lamps and fixtures for a given result.
Upstream	Lamp and fixture may be subjected to less moisture. May be the only location to apply fixtures. Fewer lamps and fixtures may be needed than on downstream side.	May not allow enough space to install fixtures. May initially take longer to clean coil and may not disinfect drain pan.

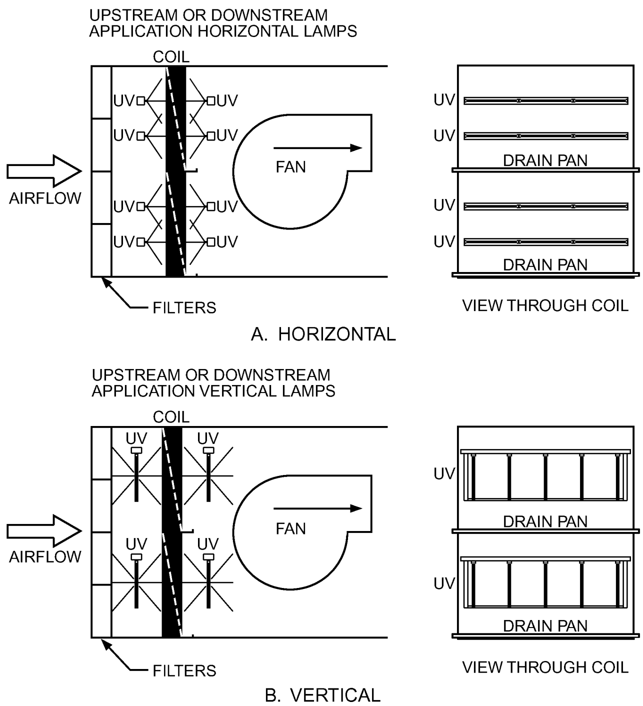


Fig. 7 UV Lamps Upstream or Downstream of Coil and Drain Pan

Fig. 8 Horizontal Lamp Placement for Coil Surface Disinfection

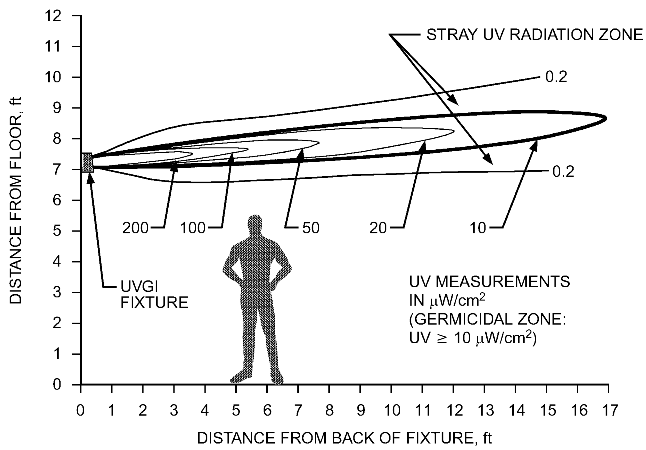


Fig. 9 Typical Elevation View

site to ensure that electrical interlocks are included to deenergize the UV system when it is accessed. UV systems should operate continuously to maximize UV's benefits and to improve lamp life, and to counteract mold and bacteria growth that occurs when an HVAC system is not operating.

UVGI systems can be installed upstream or downstream of the cooling coil (Figure 7). Both locations have advantages and disadvantages, as shown in Table 3. Figure 8 shows an actual installation at a coil.

Upper-Air UVGI Systems

Upper-air irradiation systems are designed to irradiate only air in the upper part of the room. Their narrow, focused beam is placed parallel to the plane of the ceiling and prevents stray ultraviolet rays from impinging on occupants below. Upper-air systems 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 Branch 1972). 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.

Upper-room UVGI fixtures typically use low-pressure UVC lamps in tubular and compact shapes, and require a variety of electrical wattages. Beyond lamp size, shape, and ballast, fixtures are designed to be open or restricted in distribution, depending on the physical space to be treated.

Ceiling heights above 10 ft allow more for more open fixtures, which are more efficient. For occupied spaces with lower ceilings (less than 10 ft), various louvered upper-room UVGI fixtures (wall, pendant, and corner) are available to be mounted in combinations at least 7 ft from the floor to the bottom of the fixture. Figure 9 shows some typical elevations and corresponding UV levels, and Figure 10 illustrates distribution in a room.

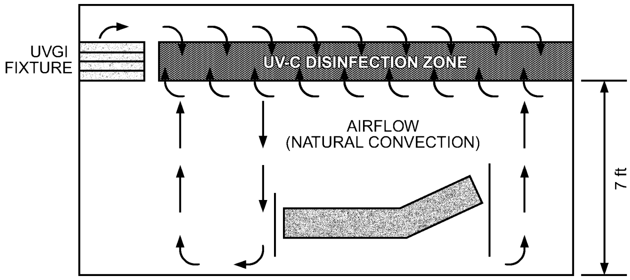


Fig. 10 Room Distribution

Application guidance with placement criteria for UV equipment is provided by Boyce (2003), CDC (2005), CIE (2003), Coker (2001), First (1999), and IESNA (2000). Additionally, manufacturer-specific advice on product operations should be followed.

A basic criterion for upper-room installations has been one 30 W (electrical input) fixture for every 18.6 m^2 (200 ft^2) (Riley et al. 1976). A UVGI installation that produces a maintained, uniform distribution of UV averaging between 30 and 50 $\mu W/cm^2$ should be 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 and Peccia 2003). Beyond UVC emission strength, effectiveness of upper-air UVGI 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 improves greatly with well-mixed air (First et al. 2007a, 2007b; Miller et al. 2002; Riley et al. 1971a, 1971b). Ventilation systems should maximize air mixing to receive the greatest benefit from upper-room UVGI. Relative humidity should be less than 60%; levels over 80% rh may reduce effectiveness (Kujundzic et al. 2007; Xu and Peccia 2003). To maintain efficient output from low-pressure UVC lamps in the upper room, room temperature should be within recommended ASHRAE *Standard* 55 guidelines for occupant comfort. For example, in high-risk areas such as corridors of infectious disease wards, a minimum of 0.4 $\mu W/cm^2$ at eye level is a good engineering guide (Coker et al. 2001). No long-term health effects of UVC exposure at levels found in the lower occupied part of rooms are known.

UV Photodegradation of Materials

The UVC energy used in HVAC applications can be very detrimental to organic materials (ACGIH 1999; Bolton 2001). As such, if the UV is not applied properly and vulnerable materials are not shielded or substituted, substantial degradation can occur (NEHC 1992). Easily degraded materials include synthetic filter media, gaskets, rubber, motor windings, electrical insulation, internal insulation, and plastic piping; many of these can degrade in days under sufficient irradiation. This degradation can result in decreased filtration efficiency, defective seals, and damaged system components, causing a loss in system performance and/or potential safety concerns. As a simple, practical approach, it is wise to shield all organic material components within about 5 ft of the UV lamp.

If materials cannot be shielded, then the UVC dose that will cause failure of the part must be determined. To ensure that materials can withstand UVC exposure over the life of the product, measure the level of UVC incident upon the part. If, over its lifetime, the part will receive a UVC dosage greater than the failure level, a more resistant material must be substituted. Materials that are located on the opposite side of the coil from the UV lamps are generally safer, because the level of UV penetrating a cooling coil is low.

Inorganic components such as metal and glass are not affected by UV. Many components that contain a lot of black coloring (lampblack), such as drive belts, are quite resistant to UV and are generally acceptable to use if UV levels are reasonable.

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 rated life of UV lamps is in the range of 6000 to 10,000 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 Disposal

UV lamps should be treated the same as other mercury-containing devices, such as fluorescent bulbs. 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 2008). 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 http://www.lamprecycle.org.

The most stringent of local, state, or federal regulations for disposal should be followed.

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 lamp 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 because of inadequate prefiltration, it should be cleaned with a lint-free cloth and commercial glass cleaner or alcohol.

Future UVGI systems may include a feedback component to alert maintenance personnel to UVC lamp output decline.

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 cornea (outer dead layer of human skin), thus minimizing the amount of UVC 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 sunburn with no 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, but is still a skin hazard.

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

Sources of UV Exposure

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

UVC energy can reflect from 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 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 clearly indicates the absence of UV energy.

Well-designed and commissioned UVGI installations, education of maintenance personnel, signage, and safety switches can avoid overexposure. During commissioning and before operation of the UVGI installation, hand-held radiometers with sensors tuned to the read the specific 254 nm wavelength should be used to measure stray UVC 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 4 lists some permissible exposure times for different levels of UVC 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 UVC 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 UVGI (ACGIH 2007).

Some plants do not tolerate prolonged UVC 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 (2007) 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:

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

UV Radiation Measurements

UV 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. 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 tubes are installed (newer tube designs may have increased irradiance)

Table 4 Permissible Exposure Times for Given Effective Irradiance Levels of UVC Energy at 253.7 nm

Permissible Exposure Time*	Effective Irradiance, μW/cm^2
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

Source: ACGIH (2007).

- Whenever modifications are made to the UVGI system or room (e.g., adjustment of fixture height, location or position of louvers, addition of UV-absorbing or -reflecting materials, room dimension changes, modular partition height changes)

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 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. Switches should be wired in series so that opening any access deenergizes the system. On/off switches 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 UVC-absorbing materials. 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 UVGI
  Caution: Ultraviolet energy. Switch off lamps before entering upper room.

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

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

- 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, are sufficient to protect eyes from UV, but not all offer complete coverage; standard-issue protective goggles may be the best alternative.

If individual lamp operating condition must be observed, this should preferably be done using the viewing 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 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 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 bulb clean-up.

If a lamp breaks in a worker's hand, the worker should not exit the HVAC equipment with the broken bulb. Carefully set the broken bulb 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 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.

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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