

Ultraviolet Germicidal Irradiation

Current Best Practices

The U.S. General Services Administration requires that UVC be included in cooling coil air-handling units for all new facilities and alteration projects to maintain coil cleanliness and improve air quality.

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Ultraviolet germicidal irradiation (UVGI) is the use of ultraviolet (UV) energy (electromagnetic radiation with a wavelength shorter than that of visible light) to kill or inactivate viral, bacterial, and fungal species. The UV spectrum is commonly divided into UVA (wavelengths of 400 nm to 315 nm), UVB (315 nm to 280 nm), and UVC (280 nm to 200 nm). The entire UV spectrum can kill or inactivate many microorganisms, but UVC energy provides the most germicidal effect, with 265 nm being the optimum wavelength.¹

Modern UV lamps primarily create UVC energy at a near-optimal 254 nm by electrical discharge through low-pressure gas (including mercury vapor) enclosed in a quartz tube. UVC from mercury lamps is sometimes referred to as UVGI to denote its germicidal properties. Although UVC is invisible to the human eye, small amounts of energy released at visible wavelengths

produce the blue glow commonly associated with UVC lamps.

Brief History

UVGI was first demonstrated to disinfect water in 1877.² In 1903, Danish physician Neils Finsen was awarded the Nobel Prize in Medicine and Physiology for his research using UV radiation for the treatment of various diseases,

including smallpox and lupus.³ During the 1930s and early 1940s, researchers experimented with UVGI to control the spread of contagious airborne diseases. In 1936, Hart successfully used UVGI to disinfect air in a Duke University hospital operating room by showing a reduction in surgical wound infections.⁴ A landmark study during the measles epidemic of 1941–1942 showed a significant reduction in infection among Philadelphia school children in classrooms where UVGI systems were installed, compared to control classrooms without UVGI.⁵

The success of these early studies provided hope that UVGI could be useful in preventing the spread of disease. Yet, successful outcomes were countered by studies showing that UVGI had little or no effect. Through much of the 1940s and 1950s, interest in UVGI applications was low. Then, in the late 1950s, Riley and O'Grady successfully used UVGI to

eliminate viable TB bacilli from the exhaust air of a hospital ward.⁶ This famous work, along with more recent studies documenting the effectiveness of UVGI⁷ have contributed to the renewed enthusiasm regarding UVGI applications that we see today.

Government agencies and the HVAC community are increasingly aware of the benefits of UVGI applications. The U.S. General Services Administration requires that UVC be included in cooling coil air-handling units for all new facilities and alteration projects to maintain coil cleanliness and improve air quality.⁸ The Centers for Disease Control and Prevention supports the use of UVGI as an adjunct to mechanical ventilation and filtration to prevent and control the spread of tuberculosis.⁹ Similarly, the Federal Emergency Management Agency¹⁰ and Environmental Protection Agency (EPA)¹¹ note that UVGI technologies can be used to provide protection against bioterrorism.

UV Dose and the Microbial Response

UVGI effectiveness depends primarily on the UV fluence or dose (D_{UV} , $\mu\text{J}/\text{cm}^2$) delivered to the microorganisms:

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

where I is the average fluence rate or irradiance in $\mu\text{W}/\text{cm}^2$, and t is the exposure time in seconds (Note: $1 \text{ W} = 1 \text{ J/s}$). Although Equation 1 seems quite simple, its application can be complex, for example, when calculating the dose received by a particle following a tortuous path through a device in which the fluence rate varies spatially. The dose is interpreted as that occurring on a single pass through the device. Although the effects of repeated exposure of microorganisms entrained in recirculated air may be cumulative, this effect has not been quantified and it is conservative to neglect it.

The survival fraction (S) of a microbial population exposed to UVGI is an exponential function of dose:

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

where k is a species-dependent deactivation rate constant ($\text{cm}^2/\mu\text{J}$). The resulting single pass inactivation rate (η) is the complement of S :

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

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

Measured k -values for many species of bacteria and fungi have been published in scientific literature. As shown in Figure 1, bacteria are generally more susceptible to UVGI than fungi, but this is not always the case. Reported k -values for different species of bacteria and fungi vary over orders of magnitude. Consequently, choosing which k -value to use is often difficult and confusing. The variation in reported k -values makes gen-

eralizing the use of Equation 2 for heterogeneous microbial populations complicated. Even accurately determining S for one specific microorganism can be difficult, as the reported k -values for the same species sometimes differ significantly. For example, published k -values for *Mycobacterium tuberculosis* irradiated in air range from $0.077309 \text{ cm}^2/\mu\text{J}$ down to $0.002132 \text{ cm}^2/\mu\text{J}$.^{6,12}

Variation of measured k -values may relate to differences in conditions under which UV irradiance was conducted (air, water, surface), methods used to measure the irradiance level, and errors relating to culture-based measurements of microbial survival. Research to obtain reliable k -values for UV system design is ongoing. In the meantime, systems are usually designed conservatively using an average or worst-case value, depending on the disinfection goals.

UVGI Design Guidelines

UVGI system design from the early 1900s until recent times was more art than science, as there were limited design criteria to follow. During the last half-century, the scientific community has gained a better understanding of how UVGI inactivates microorganisms. UVC lamp technology improved dramatically over this same period. Unfortunately, UVGI system design has not advanced at the same rate. Some of the first guidelines for UVGI air-disinfection system designs were published in the 1940s. Additional guidelines published by General Electric (1950) and Philips (1985) are still used by many system designers today.^{13,14} More recently, Kowalski and others have made meaningful advances in the analysis and modeling of UVGI systems that have improved guidance for system design.¹⁵ However, no consensus guidelines yet exist that comprehensively address all aspects of UVGI system design required to ensure good performance.

UVGI system design today relies on performance data from lamp manufacturers, the experience of system designers, and the recommendations of UVGI equipment manufacturers. Most equipment manufacturers have detailed methods for estimating the UV dose delivered, which may include using tabulated data charts, mathematical modeling, and complex formulas. Like most HVAC components, UVGI systems are typically oversized

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to ensure performance. While oversizing may be conservative, there is the potential for increased equipment costs, increased utility costs, and wasted energy. As with any system, a balance must be struck between performance and price.

UVGI Standards

Although application support for UVGI technologies is growing and many successful systems have been installed, there are still no industry standards for rating the effectiveness of UVGI devices and systems. A recent EPA publication stated: "The most important needs in the area of UVGI are industry standards to rate devices and installations, as well as guidance for installation and maintenance."¹¹ ASHRAE and others are working to meet these needs. In 2003 the ASHRAE technical activities committee approved a task group to focus on ultraviolet air and surface treatment (TG2.UVAS), which became standing Technical Committee (TC) 2.9 in 2007. Also in 2003, ASHRAE approved the formation of a standards project committee (SPC-185) to develop testing standards for UVGI air (185.1) and surface (185.2) disinfection systems. Both standards are under development.

Current Best Practices for Common UVGI Configurations

This year, a new chapter on UVGI technologies was published in the *ASHRAE Handbook—HVAC Systems and Equipment*.¹ The information presented in the handbook chapter draws from the pertinent scientific literature and the collective experience of engineers, lamp manufacturers, and system designers familiar with UVGI applications. The result is a current best practices guide for common UVGI systems used with mechanical ventilation systems to disinfect air-handling unit (AHU) surfaces, improve indoor environmental quality, and to reduce the likelihood of airborne disease transmission. A summary of the current best practices for in-duct and upper-air UVGI systems detailed in the new Handbook chapter is presented here.

In-Duct UVGI

In-duct UVGI systems, as the name implies, are installed inside ventilation ductwork or inside AHUs (Figure 2). When selected to produce appropriate irradiance levels, in-duct systems are effective for surface and air disinfection. The goal of surface disinfection is to reduce or eliminate microbial growth on internal surfaces of HVAC systems, typically cooling coils and drain pans. The goal of air disinfection is "on-the-fly" inactivation of microbes suspended in the air as it moves through the duct or AHU.

In-duct UVGI should always be used in combination with filtration. Filters help protect UV lamps from dust that may reduce UV output, and enhances the air cleaning capabilities

More Susceptible	Organism Group	Member Group
Vegetative Bacteria	Vegetative Bacteria	<i>Staphylococcus aureus</i>
		<i>Streptococcus progenies</i>
		<i>Escherichia coli</i>
		<i>Pseudomonas aeruginosa</i>
		<i>Serratia marcescens</i>
Mycobacteria	Mycobacteria	<i>Mycobacterium tuberculosis</i>
		<i>Mycobacterium bovis</i>
		<i>Mycobacterium leprae</i>
Bacterial Spores	Bacterial Spores	<i>Bacillus anthracis</i>
		<i>Bacillus cereus</i>
		<i>Bacillus subtilis</i>
Fungal Spores	Fungal Spores	<i>Aspergillus versicolor</i>
		<i>Penicillium chrysogenum</i>
		<i>Stachybotrys chartarum</i>
Less Susceptible		

Figure 1: General ranking of susceptibility of various organism groups to UVC inactivation with examples of species from each group.

of the system. Filters remove larger microbes like fungal spores that are more resistant to UVGI, while UV inactivates more susceptible organisms like bacteria and viruses. It is recommended that the highest-rated filter the fan motor can handle be used, while still providing adequate airflow to the space.

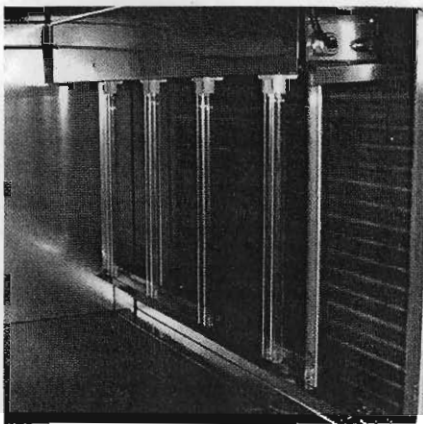


Figure 2: Typical in-duct UVGI installation with lamps mounted downstream of the cooling coil and drain pan.

Surface Disinfection

When applying in-duct UVGI for surface disinfection, it is best to start with clean surfaces. Coils and drain pans should be cleaned, especially if there is coil fouling or microbial growth. UVGI is applied by mounting UVC lamps in proximity to the cooling coils and spacing lamp fixtures to allow an even distribution of energy. Reflectors may be used to focus UV energy onto the surface (Figure 3). Fixture arrangement tools or design recommendations are available from most manufacturers to aid in outfitting larger systems. Lamps may be mounted on the upstream or downstream side of the coil

and at any angle, as UV energy will penetrate into the fins from either direction. It is often better to locate fixtures downstream of the coil because of space availability, and mounting lamps downstream often provides improved irradiation of the drain pan.

While the exact mounting location of the lamps is dependent on the AHU design and the particular lamps used, mounting lamps within 3 ft (0.9 m) of the coil is common practice, and the lamps are generally operated 24 hours per day, seven days

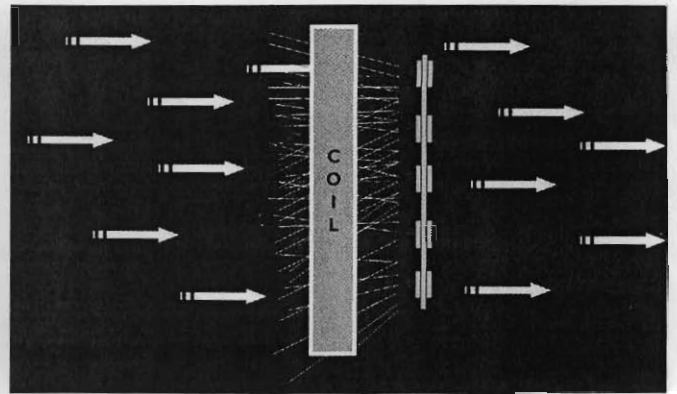
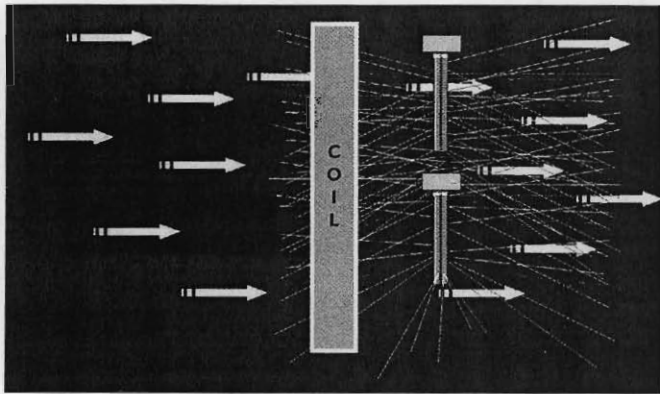


Figure 3 (left): Typical in-duct UVGI installation for surface disinfection. Reflectors are used to focus the UV energy on the surface(s) of interest. Figure 4 (right): Typical in-duct UVGI installation for air disinfection. Reflectors are not used, so the UV energy can be distributed throughout the air path. Air disinfection systems mounted within 3 ft (0.9 m) of surfaces are capable of disinfecting the air and surfaces simultaneously.

per week. Continuous exposure allows for a UV dose effective at preventing microbial growth on surfaces at relatively low levels of irradiation.

Air Disinfection

Because reflectors focus UV energy onto the surface to be cleaned, surface disinfection systems are often inadequate for proper air disinfection. On the other hand, properly designed

air disinfection systems are capable of disinfecting air while maintaining surface cleanliness. These systems usually do not have reflectors or lamp ballast assemblies that block UV energy (Figure 4). Instead, enhancing the overall reflectivity of the inside of the duct or AHU can improve system performance by reflecting UVC energy back into the irradiance zone, increasing the effective UV dose. Regardless of the design, the principle objective is to distribute UV energy in all directions throughout

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the length of the duct or AHU to achieve longer exposure times as air moves through the irradiated zone.

In-duct air disinfection systems, frequently installed in air-handling units, are typically designed for an air velocity of around 500 ft/min (2.5 m/s), although systems can be installed in air ducts where the velocity is much higher. At 500 ft/min (2.5 m/s), an irradiance zone of 8 ft (2.4 m) in length achieves a one second exposure. The UV dose required to inactivate a microorganism is the same whether it is on a surface or is in a moving airstream. To compensate for shorter exposure times, air disinfection systems require higher irradiance levels than surface disinfection systems. This translates to higher output lamps, more lamps within the duct, sufficient reflectivity, a method that allows air to be exposed to UVC over a longer air path, or any combination of these.

At 500 ft/min (2.5 m/s), air-disinfection systems should be placed in an area where they can achieve a 2 ft (0.6 m) minimum irradiation zone down the length of the duct. This will provide roughly 0.25 seconds of exposure time and the UVGI system should be sized to deliver a sufficient dose to inactivate the airborne microorganisms of interest within that time period. UVGI fixtures are most often located downstream of the heating/cooling coils. However, in some cases mounting fixtures upstream of the coil may result in lower air velocity and/or

increased UVC exposure time for "on-the-fly" inactivation. The trade-off is forgoing the disinfection of the drain pan that lamps mounted downstream of the coil also provide.

In-duct air disinfection systems used to reduce or eliminate the spread of airborne infectious diseases (e.g., tuberculosis or influenza) in buildings with continuous occupancy and/or with immunocompromised populations (e.g., hospitals, prisons, or homeless shelters) should be operated on a continuous basis. However, properly designed systems installed in more traditional commercial buildings (e.g., offices or retail) can be operated intermittently, for example, powered on during hours of normal building occupancy and powered off when the facility is empty. This may result in energy savings and require less frequent lamp replacement while providing acceptable indoor air quality during periods of occupancy. Intermittent operation must be factored into the initial system design, as cycling UV lamps on and off is one of the many variables that affect lamp output and life.

Upper-Air UVGI

Upper-air UVGI involves lamp fixtures suspended from the ceiling and/or installed on walls with the fixture bottom at least 7 ft (2.1 m) above the floor (Figure 5). Lamps are shielded to direct radiation upward and outward to create an intense zone of UV in the upper portion of the room while minimizing UV

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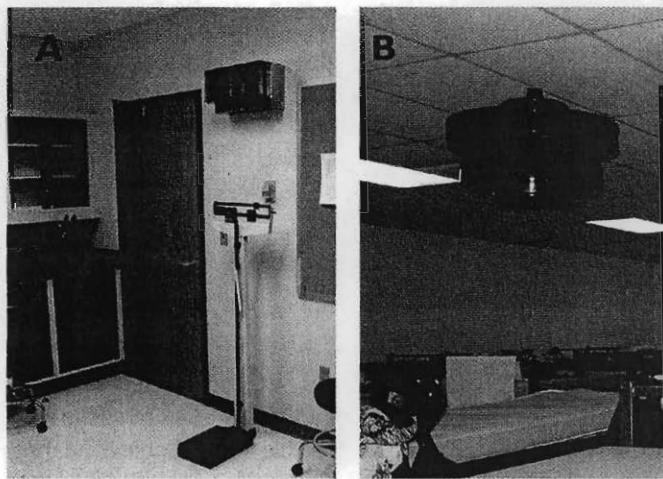


Figure 5: Typical upper-air UVGI installations. Figure 5a (left): Wall-mounted fixture in a health clinic. Figure 5b (right): Ceiling-mounted fixture in a homeless shelter.

levels in occupied spaces (Figure 6). These fixtures inactivate airborne microorganisms by irradiating them as air currents move them into the path of the UV energy. Some louvered fixtures use small fans to enhance air mixing (Figure 5b), which is a critical component of overall effectiveness.

Where an in-duct UVGI system may not be feasible, or where additional UVGI is desired to further reduce airborne infectious disease transmission, upper-air systems can provide an effective solution. Application and placement criteria for upper-air UV fixtures are provided in various publications, and manufacturer-specific advice on placement and operations should always be followed. A rule of thumb for upper-air installations has been one 30 W (nominal input) fixture for every 200 ft² (18.6 m²) of floor space to be irradiated.¹⁶ Many effective systems have been designed to this criterion, yet it is important to note that not all 30 W lamps provide the same output of UVC energy. UVC output is dependent on the type of lamp, the lamp manufacturer, and various other factors. Recent studies have suggested installing fixtures to maintain a uniform UV distribution of around 30 $\mu\text{W}/\text{cm}^2$ to 50 $\mu\text{W}/\text{cm}^2$ in the upper portion of the room.¹⁷ While essentially “normalizing” the recommended output over all lamps, this level of irradiance should be effective at inactivating most airborne droplet nuclei containing *Mycobacterium*, and would presumably be effective for inactivation of most viruses as well.

The overall effectiveness of upper-air UVGI systems improves significantly when the air within the space is well mixed. Although convection air currents created by occupants and equipment can provide adequate air circulation in some settings, mechanical ventilation systems that maximize air mixing are preferable. If air mixing with mechanical ventilation is not possible, fans can be placed in the room to ensure adequate mixing.

General UVGI System Design Parameters

In addition to those criteria mentioned previously, many other parameters should be considered when designing or selecting a UVGI system. The most important are discussed below.

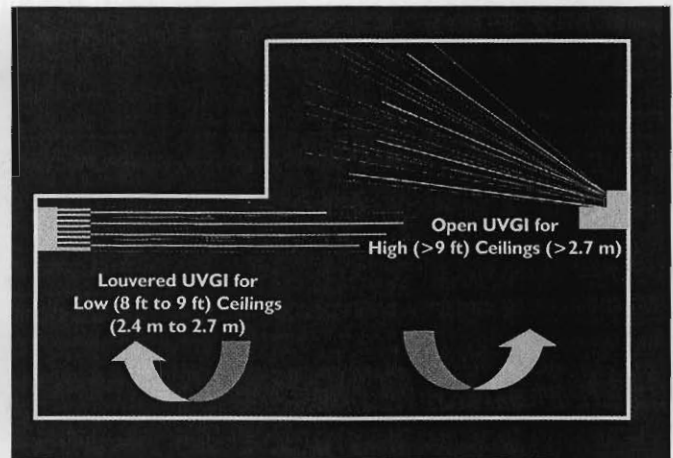


Figure 6: Typical upper-air UVGI installation showing wall mounted fixtures. Depending on the ceiling height, louvered fixtures or open fixtures are used to irradiate the air in the upper portion of the room while maintaining UV levels in the lower, occupied space at safe levels. Convection air currents and/or mechanical ventilation moves air through the irradiated zone. Ceiling-mounted fixtures can also be used.

Relative Humidity

Relative humidity (RH) has no significant impact on the performance of UV lamps, and its effect on the susceptibility of microorganisms (k-value) is not well understood. Attempts to correlate susceptibility of microorganisms to RH have yielded inconsistent results but it appears to be organism specific.^{18,19} The relationship between RH and k-values seems complex, but most research reported effects only as RH values increased above 70%. It is recommended that UVGI systems be operated below 60% RH, which is consistent with recommendations from ASHRAE and other organizations for providing comfort, acceptable indoor air quality, and minimizing indoor microbial contamination. Most upper-air UVGI systems are operated where the relative humidity is maintained below 60%. Conversely, in-duct systems are frequently operated at higher humidity levels. Depending on the disinfection goals for an in-duct system, potential effects of high RH levels on inactivation efficiency may need to be explored in more detail.

Air Temperature and Velocity

Air temperature and velocity generally do not affect microorganism susceptibility to UVGI. However, their combined effect on lamp temperature can cause significant variation in lamp output, and ultimately UV dose. Depending on the lamp used, the UV output for in-duct systems can vary by more than 60% across a range of temperature and velocity conditions typical of HVAC system operation, particularly in VAV systems where both can change simultaneously.²⁰ Modern UVC lamps are designed to reduce the output variation experienced by lamps designed to operate at room temperatures and still-air conditions when they are used for in-duct applications. The impact of air temperature and velocity should be considered in the design of in-duct systems to ensure that desired performance is maintained across

all operating conditions. Output variation due to air temperature and velocity is not a concern for most upper-air systems.

Reflectivity

In-duct systems benefit from increasing UVC reflectivity within the ductwork. Reflection can be an economical way to increase UVGI intensity because reflected energy adds to direct energy in determining UV dose. While a surface may reflect visible light, it may not reflect UVC energy. For instance, polished brass reflects most visible light, but less than 10% of UVC. Galvanized duct material has a UVC reflectivity of around 55%. Aluminum and other reflective materials may be used to line ducts to improve effective irradiation levels. System designers and manufacturers can provide information on improving reflectivity for UVGI in-duct applications.

Although reflectivity is desirable for in-duct systems, it could be a safety concern with upper-air systems. Properly designed upper-air fixtures virtually eliminate UV reflections from ceilings or opposing walls located more than 10 ft (3 m) from the outward opening of the fixture. Yet, there may be times when fixtures must be mounted in suboptimal positions. Reflections from walls and ceilings can be minimized with low UV-reflectance paint or wall coverings while maintaining adequate irradiation in the upper air and limiting UV exposure to people in the room.

UV Degradation

Inorganic materials like metal and glass are not affected by normal exposure to UVC energy, but organic materials can rapidly degrade. Organic materials, such as synthetic filter media, gaskets, rubber, motor windings, electrical insulation, internal duct insulation, and plastic piping, within 6 ft (1.8 m) of in-duct lamps should be shielded with UV-resistant materials. Failure to shield these materials can lead to damaged system components resulting in reduced performance and/or safety concerns.

Degradation of system components is usually not a concern with upper-air systems. Building materials can degrade if wall or ceiling paint is cracked or peeling. Books, paper, and other items stored in the upper-portion of a room may suffer from discoloration and deterioration. Plants being wilted by upper-air UVGI systems have also been reported. While not desirable, these problems can be prevented easily by proper maintenance and by locating susceptible items outside the irradiated zone.

Conclusions

Although support for the technology is growing, the industry still lacks design guidance applicable to all UVGI systems and standards for testing the effectiveness of individual devices and complete systems. Until this information becomes available, systems should be sized and designed using the best available information, which has been briefly summarized here. More detailed information can be found in the new chapter on UVGI technologies published for the first time in the 2008 *ASHRAE Handbook—HVAC Systems and Equipment*. Similar UVGI chapters will be added to the other ASHRAE Handbook volumes during subsequent revisions.

References

1. 2008 *ASHRAE Handbook—HVAC Systems and Equipment*, Chapter 16.
2. Downes, A. and T.P. Blount. 1877. "Research on the effect of light upon bacteria and other organisms." *Proceedings of the Royal Society of London* 26:488–500.
3. The Nobel Foundation. <http://tinyurl.com/6m8u7p> (or http://nobelprize.org/nobel_prizes/medicine/laureates/1903/finsen-bio.html) (accessed June 17, 2008).
4. Hart, J.D. 1936. "Sterilization of air in operating room by special bactericidal radiant energy." *Journal of Thoracic Surgery* 6:45–81.
5. Wells, W.F., M.W. Wells and T.S. Wilder. 1942. "The environmental control of epidemic contagion. I: An epidemiologic study of radiant disinfection of air in day schools." *American Journal of Hygiene* 35:97–121.
6. Riley, R.L. and F. O'Grady. 1961. *Airborne Infection: Transmission and Control*. New York: Macmillan.
7. Menzies, D., et al. 2003. "Effect of ultraviolet germicidal lights installed in office ventilation systems on workers' health and wellbeing: double-blind multiple crossover trial." *The Lancet* 362:1785–1791.
8. U.S. General Services Administration. 2005. PBS-P100, *Facilities Standards for the Public Buildings Service*.
9. U.S. Department of Health and Human Services/Centers for Disease Control and Prevention. 2005. "Guidelines for preventing the transmission of *Mycobacterium tuberculosis* in health-care settings, 2005." *Morbidity and Mortality Weekly Report* 54(RR-17).
10. U.S. Department of Homeland Security/Federal Emergency Management Agency. 2003. FEMA 426, *Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings*.
11. U.S. Environmental Protection Agency. 2007. EPA 600/R-07/157, *Building Retrofits for Increased Protection Against Airborne Chemical and Biological Releases*.
12. Collins, F.M. 1971. "Relative susceptibility of acid-fast and non-acid-fast bacteria to ultraviolet light." *Applied Microbiology* 21:411–413.
13. General Electric Engineering Division, Lamp Department. 1950. "Bulletin LD-11, Ultraviolet Air Sanitation."
14. Philips Lighting Division. 1985. *Germicidal Lamps and Applications*.
15. Kowalski, W.J. and W.P. Bahnfleth. 2000. "Effective UVGI system design through improved modeling." *ASHRAE Transactions* 106(2):4–15.
16. Riley, R.L. and E.A. Nardell. 1989. "Clearing the air: the theory and application of ultraviolet disinfection." *American Review of Respiratory Disease* 139:1286–1294.
17. Xu, P., et al. 2003. "Efficacy of ultraviolet germicidal irradiation of upper-room air in inactivating airborne bacterial spores and mycobacteria in full-scale studies." *Atmospheric Environment* 37:405–419.
18. Peccia, J., H.M. Werth, S. Miller and M. Hernandez. 2001. "Effect of relative humidity on the ultraviolet induced inactivation of airborne bacteria." *Aerosol Science and Technology* 35:728–740.
19. Air Conditioning and Refrigeration Technology Institute. 2002. "Report ARTI-21CR/610-40030-01, Defining the Effectiveness of UV Lamps Installed in Circulating Ductwork."
20. Lau, J., W. Bahnfleth and J. Freihaut. 2007. "Predicted performance of in-duct UVGI systems under variable operating conditions." *Proceedings of IAQ 2007—Healthy and Sustainable Buildings*.

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