Virus Transmission Modes and Mitigation Strategies, Part 3

Ventilation, Filtration And UVGI

BY JONATHAN BURKETT, P.E., HFDP, MEMBER ASHRAE

Parts 1 and 2 of this article in the March and April 2021 issues of *ASHRAE Journal* focused on viral infection, transmission and propagation in a space. Part 3 will focus on popular virus mitigation strategies and their application to single zone HVAC systems.

Ventilation (Dilution)

The need for ventilation for good indoor air quality in buildings has been recognized throughout history. Natural ventilation has been used for centuries to ventilate smoke, dust and odors. During the Crimean and U.S. Civil War, physicians observed that wounded soldiers fared better when they were housed in tents or barns (allowing greater ventilation) rather than crowded hospitals with poor ventilation.[1] ASHRAE Standard 62.1-2019 defines ventilation air as "that portion of supply air that is outdoor air plus any recirculated air that has been treated for the purpose of maintaining acceptable IAQ."[2] The Wells-Riley equation (see Part 1[3]) shows that by increasing the ventilation air rate, the infection risk can be reduced significantly.[4,5]

The equation of ventilation (*Figure 1*) shows the basic relationship between ventilation rate and concentration. Like the Wells-Riley equation, the equation of ventilation is also based on a fully mixed room and shows that the higher the ventilation rate, the more rapid the decay of droplet nuclei in the room.[5] Research by Li, et al., that reviewed over 40 studies concerning ventilation and airborne infection, found "strong and sufficient evidence to demonstrate the association between ventilation and the control of airflow directions in buildings and the transmission and spread of infectious diseases such as measles, TB, chicken pox, anthrax, influenza, smallpox and SARS."[6]

In their "Guidelines for Environmental Infection Control in Health-Care Facilities," the Centers for Disease Control and Prevention (CDC) lists the theoretical time for 99% and 99.9% removal of airborne contaminants based on air changes per hour (ach) (*Table 1*).[7] The values in *Table 1* are based on the airborne contaminant removal formula (*Figure 2*) and show the time to reach the listed percent removal after the generation of the contaminant is finished. Looking at an example classroom (*Figure 3*), the outdoor air ventilation rate is 3.5 ach.

Using the airborne contaminant removal formula, 99% removal can be achieved in 79 minutes or 99.9% removal in 118 minutes. This example assumes that

Jonathan Burkett, P.E., is a mechanical engineer at Buford Goff & Associates in Columbia, S.C.

This peer-reviewed article does not represent official ASHRAE guidance. For more information on ASHRAE resources on COVID-19, visit ashrae.org/COVID19.

FIGURE 1 The equation of ventilation shows the basic relationship between ventilation rate and concentration.[5]

Equation of ventilation:

$$V\frac{dc}{dt} = q(c_o - c) + \dot{V}_{pol}$$

General solution for equation of ventilation:

$$c = (c_o - c_G)(1 - e^{-nt}) + c_I e^{-nt}$$

V = Volume of space (m^3)
c = Concentration (% or kg/m^3)
q = Ventilation rate (m^3/s)
c_o = Supply air concentration (% or kg/m^3)
dc= Change in concentration
dt= Change in time
$\dot{V}_{pol}$ = Pollutant generation rate in the room (m^3/s or kg/m^3)
$c_G = \frac{\dot{V}_{pol}}{q}$ = source concentration
c_I = Initial concentration at time $t = 0$
n = Air change rate

TABLE 1 Airborne contaminant removal in a fully mixed, empty room with no aerosol-generating source.

ACH	TIME (MIN) REQUIRED FOR REMOVAL (99% EFFICIENCY)	TIME (MIN) REQUIRED FOR REMOVAL (99.9% EFFICIENCY)
2	138	207
4	69	104
6	46	69
8	35	52
10	28	41
12	23	35
15	18	28
20	14	21
50	6	8

Note: Data taken from CDC's "Guidelines for Environmental Infection Control in Health-Care Facilities," Appendix B.[7]

FIGURE 2 Airborne contaminant removal formula.[7]

$$t_2 - t_1 = -\left(\frac{\ln\left(\frac{C_2}{C_1}\right)}{\frac{Q}{V}}\right)\times 60 = -\left(\frac{\ln\left(1-\frac{E_r}{100}\right)}{\text{ach}}\right)\times 60, \text{where } t_1 = 0$$

t_1 = Initial time (min)
V = Volume of space (ft^3)
Q = Airflow rate in ft^3/h
E_r = Removal efficiency
t_2 = Final time (min)
C_1 = Initial contaminant concentration
C_2 = Final contaminant concentration

the outdoor air is free from contaminants, the filtration effectiveness is low enough to ignore and that there is perfect mixing in the space. If the outdoor air is increased 150%, then the time to get to 99% removal can be decreased to 52 minutes. These guidelines can be used to determine flush times between classes or before starting the school day. However, the assumption of perfect mixing in the space is usually not accurate. Stagnant areas caused by the air distribution system can increase the removal time.

The airborne contaminant removal formula shows that 63% of the airborne contaminants will be removed with each air change, but a more realistic range has been shown to be 20% to 60%.[8] ASHRAE's Building Readiness Guide recommends that spaces be flushed for a duration sufficient to reduce the concentration of airborne infectious particles by 95% between occupancy, which equates to about three changes of space volume using equivalent outdoor air for a well-mixed space.[9]

A study by Qian, et. al., determined that in general "increasing [the] ventilation rate can effectively reduce the risk of long-range airborne transmission."[4] As mentioned above, Li, et al., also found strong evidence to demonstrate the association between ventilation and the spread of infectious diseases.[6] The World Health Organization (WHO) in their *Natural Ventilation for Infection Control in Health-Care Settings* study found that low ventilation rates can result in increased infection.[5] While all of these studies point to the importance of ventilation, minimum clean air rates to prevent infection have not been established.[4–6] Also, as mentioned in previous parts of this article, ventilation rates have little effect on large droplet-borne transmission.[4] The presence of pathogens in the room is only one of the susceptibility factors involved in the infection process (see Part 1[3]), which further complicates determining a minimum ventilation rate for these spaces.

While the Wells-Riley equation shows that increasing the ventilation rate will also decrease the infection risk, this relation may not apply uniformly across a space. A study by Memarzadeh, et al., shows the importance of the path between the contaminant source and the exhaust in a patient room.[10] The study determined that increasing the ventilation rate from 4 ach to 12 ach had little impact on the infection risk in their model when the exhaust was not located directly over the patient's head. Other studies have also shown that increasing

FIGURE 3 High school classroom.

Room area = 800 ft^2
Ceiling height = 10 ft
Number of students = 27
Number of teachers = 1
Room is served by a 3 ton unit at 1,200 cfm

Room uses overhead mixing ventilation with E_z = 0.8
Table 6-1 in ASHRAE Standard 62.1-2019, people outdoor air rate = 10, and the area outdoor air rate = 0.12

$$V_{bz} = R_p P_z + R_a A_z = 10 \times 28 + 0.12 \times 800 = 376 \text{ cfm}$$

$$V_{ot} = V_{oz} = \frac{V_{bz}}{E_z} = \frac{376}{0.8} = 470 \text{ cfm OA}$$

$$\text{ach} = \frac{470 \text{ cfm} \times 60 \text{ min}}{800 \text{ ft}^2 \times 10 \text{ ft}} = 3.5 \text{ ach}$$

V_{bz} = Outdoor airflow required in the breathing zone (cfm)
R_p = Outdoor airflow rate required per person (cfm/person)
P_z = Zone population
R_a = Outdoor air rate required per unit area (cfm/ft^2)
A_z = Zone floor area (ft^2)
V_{ot} = Outdoor air intake flow (cfm)
V_{oz} = Zone outdoor airflow (cfm)
E_z = Zone air distribution effectiveness

ventilation rates to 12 ach does not necessarily reduce the infection risk (from coughing) for mixing ventilation.[11,12] These studies show the importance of distance and direction of cough in spaces.

A study by Nardell, et al., predicted the number of infected occupants in an office based on 67 susceptible subjects exposed for 160 hours to one source case generating from 1.25 to 250 infectious quanta per hour (qph).[13] At 1.2 qph, providing more than 15 cfm (7 L/s) of outdoor air ventilation per occupant produced very little decrease in infection. At 13 qph, increasing from 10 cfm (7 L/s) to 25 cfm (12 L/s) per person would reduce the infection rate by one-third, while decreasing from 10 cfm (7 L/s) to 5 cfm (2.4 L/s) per person would increase the infection rate by 78%. Increasing the rate from 25 cfm (12 L/s) to 35 cfm (17 cfm) reduced the infection rate by another 19%, and further increases in the outdoor air ventilation produced progressively smaller reductions in infection.[13] As the quanta generation rate increased, ventilation offered progressively less protection.

Table 2 shows quanta generation rates for various organisms.[14] A study by Liao, et al., delves deeper into the subject and provides a model for evaluating various control methods and the resulting number of infections that could occur.[15]

TABLE 2 Quanta generation rates.[14]

INFECTIOUS DISEASE	REPORTED QUANTA GENERATION RATES
Rhinovirus (Common Cold)	~1 to 10 Per Hour
Tuberculosis	~1 to 50 Per Hour
SARS	~10 to 300 Per Hour
Influenza	~15 to 500 Per Hour
Measles	~570 to 5,600 Per Hour

Filtration (Cleaning)

It may not always be practical to increase the outdoor air ventilation rate. Filtration can allow you to provide increased ventilation rates without increasing the outdoor air. Filters use five main mechanisms for particle collection:[16,17]

1. Straining: Particles larger than the filter's openings are removed from the airstream and deposited on the filter surface.
2. Interception: Particles that come within one radius of the fiber's surface and have sufficient contact time with the fiber can adhere to it.
3. Inertial impaction: Large or dense particles that have enough inertia to deviate from the airstream path when it encounters a flow curvature can directly impact onto a fiber's surface and adhere to it.
4. Diffusion: small-diameter particles are susceptible to Brownian motion and are knocked off the airstream path by molecular collisions, bringing them close enough to the media fibers to be captured by interception.
5. Electrostatic effects: particle or media electrostatic charges can produce a strong attracting force when they have opposite charges.

High efficiency particle air (HEPA) filters originated during World War II. The U.S. military needed a filter that would protect against chemical, biological and radiological warfare agents and contain emissions from nuclear weapons production facilities.[18,19] The earliest filters were made from the same filter paper used in gas masks of that time.[18,19]

HEPA filters use different mechanisms for capture for different particle sizes. For particles less than 0.1 µm, diffusion is the primary method.[17] For particles greater than 1 µm, inertial impaction and interception are the primary methods.[17] In both of these cases, the HEPA filter efficiency is close to 100%.[17] Between 0.1 µm and

1 µm the filter efficiency takes a dip down to 99.97% (due to the effects of diffusion tapering off before inertial impaction and interception begin to dominate), with the most penetrating particle size (MPPS) occurring between 0.2 µm and 0.3 µm.[17]

Particle penetration through the filter is greatly affected by the flow velocity. A general rule of thumb is by reducing the filter velocity by half, the pressure drop is reduced by half, and the particle penetration is reduced by almost an order of magnitude.[17]

HEPA filter test methods are typically specified by the Institute of Environmental Sciences and Technology's (IEST) IEST-RP-CC001 and IEST-RP-CC007, the International Organization for Standardization's (ISO) ISO 29463-5:2011, or the European Committee for Standardization's (CEN) EN 1822:2009. A true HEPA filter will have verified performance according to a reputable standard. However, many filters are sold as "HEPA" filters that are not tested according to one of these standards and may fall short on performance.

Unlike HEPA filters, other commercial filters are rated according to ASHRAE Standard 52.2 and assigned a minimum efficiency reporting value (MERV) between 1 and 16. ASHRAE Standard 52.2-2017 provides the particle size efficiency for three different size ranges (*Table 3*).[20] Studies have shown that the majority of virus particles expelled during cough events (80% to 90%) are smaller than 1 µm to 2 µm in diameter, but recent studies have also looked at these particles after they have been expelled from the body and the size-fractions where viruses are present.[14]

Research by Azimi, et al., reviewed several studies where influenza virus samples were captured in various indoor environments and found a mean distribution that was then applied to the ASHRAE ranges in ASHRAE Standard 52.2.[14] The mean viral distribution from the studies resulted in 20% in the 0.3 µm to 1 µm range, 29% in the 1 µm to 3 µm range and 51% in the 3 µm to 10 µm range.[14]

Research by Zhang, et al., studied the viral performance of high-efficiency electrically charged residential type filters.[21] His tests showed that the MERV 12 filters that were tested had a mean viral filtration efficiency of 78%, MERV 13 of 89%, and MERV 14 of 97%. MERV 5 was used for comparison and had a mean efficiency of 32%.[21] These efficiencies are dependent on viral load and airflow conditions, but generally show an increase in performance the higher the MERV rating.

TABLE 3 Minimum efficiency reporting value (MERV) performance.[20]

MERV	Composite Average Particle Size Efficiency, % in Size Range		
	Range 1 (0.3 µm to 1.0 µm)	Range 2 (1.0 µm to 3.0 µm)	Range 3 (3.0 µm to 10.0 µm)
8	N/A	$20 \le E_2$	$70 \le E_3$
9	N/A	$35 \le E_2$	$75 \le E_3$
10	N/A	$50 \le E_2$	$80 \le E_3$
11	$20 \le E_1$	$65 \le E_2$	$85 \le E_3$
12	$35 \le E_1$	$80 \le E_2$	$90 \le E_3$
13	$50 \le E_1$	$85 \le E_2$	$90 \le E_3$
14	$75 \le E_1$	$90 \le E_2$	$95 \le E_3$
15	$85 \le E_1$	$90 \le E_2$	$95 \le E_3$
16	$95 \le E_1$	$95 \le E_2$	$95 \le E_3$

Note: Data taken from ASHRAE Standard 52.2-2017 Table 12-1.

The filter efficiencies listed above are single-pass filter efficiencies. These filter efficiencies can be added to a contaminant generation model or an infection risk assessment model to make some general observations. A study by Mousavi, et al., looked at filter efficiencies and compared contaminant decay time to various outdoor air ratios (10% to 100%).[22] The study showed that for low filter efficiencies (MERV 12 and under) introducing additional outdoor air into the space significantly lowered the contaminant decay time. For MERV 13, 14, 15 the decay time was only slightly affected by additional outdoor air; and for HEPA filters, additional outdoor air didn't affect the decay time.[22]

A study by Bohanon looked at several different scenarios involving an infected person and the risk of infection for others in the same residence.[23] The study found that by improving the filtration in the system (up to MERV 14), the risk of infection to others in the house could be lowered by two-thirds. MERV 11 filters also performed well and were able to provide protection within a few percentage points of the MERV 14s.[23] A study by Azimi, et al., modeled a hypothetical office building with 25 occupants and a single infector.[14] The relative risk of infection was compared to the annual cost of filtration. MERV 13 and MERV 14 filters achieved the optimal combination of low risk at reduced costs. For the office building, HEPA filtration only offered incremental advantage over MERV 13 through MERV 16 at 1.6 to 2.3 times the cost of operation.[14]

As filters start to accumulate buildup, their efficiency can change. Uncharged filter media often increases in efficiency with loading, while charged-media filters often lose efficiency over time (up to 50% of the original value for small particles sizes).[24] ASHRAE Standard 52.2-2017, Appendix J provides optional calculations that can predict the decrease in efficiency for charged filter media. Note that filter loading can decrease system airflow for units with a constant speed fan.

Filter bypass can also greatly affect filter efficiency. A study by Ward, et al,. modeled the impact of filter bypass on filter efficiency.[25] The study compared two different size gaps (0.04 in. [1 mm] and 0.4 in. [10 mm]) in two different configurations and found that the effective efficiency for the 0.04 in. (1 mm) gap was close to the filter efficiency, and for the larger 0.4 in. (10 mm) gap the effective efficiency is close to zero for all submicron particles.[25] The study also calculated effective MERV ratings with bypass included. The MERV 6 filter remained a MERV 6 with a 0.04 in. (1 mm) gap, but dropped to MERV 5 with a 0.4 in. (10 mm) gap. The MERV 11 filter also remained MERV 11 with a 0.04 in. (1 mm) gap, but dropped to MERV 8 with a 0.4 in. (10 mm) gap. The MERV 15 filter dropped to a MERV 14 with a 0.04 in. (1 mm) gap and also dropped to a MERV 8 with a 0.4 in. (10 mm) gap.[25] The more efficient the filter, the greater the effect the bypass air had on the filter efficiency.

Ultraviolet Germicidal Irradiation (UVGI)

Ultraviolet germicidal irradiation (UVGI) is a method of treating air or surfaces to inactivate microorganisms. The response of microorganisms to light has been known as early as 1845, but a breakthrough came in 1877 when Downes and Blunt discovered the ability of sunlight to prevent microbial growth.[26] In 1935 Wells and Fair demonstrated the ability of UVGI to efficiently inactivate airborne microorganisms.[26] The ultraviolet (UV) spectrum is divided into UV-A, UV-B, UV-C, and vacuum UV. UV-C energy (280 nm to 200 nm) is used in UVGI with the optimal wavelength for inactivation of microorganisms occurring at 265 nm.[16] UV-C in commercial systems is typically supplied by mercury vapor lamps, which emit a near-optimal 253.7 nm.[16] UVGI effectiveness on a particular microorganism is primarily dependent on the UV dose.[27]

When treating an airstream, these UV-C lamps are placed in the air handler or ductwork with enough intensity and frequency of placement to provide the required exposure time for inactivation. The *2019 ASHRAE Handbook—HVAC Applications* recommends in-duct systems be designed to meet the desired single-pass inactivation rate (*Figure 4*) under worst-case conditions of air temperature and velocity in the irradiated zone.[27] When installed in an air-handling unit at 500 fpm (2.5 m/s), an irradiance zone 8 ft (2.4 m) in length results in a 1 s exposure.[27]

FIGURE 4 UVGI formulas.[27,28]

Survival Fraction (S):

$$S = e^{-kD_{UV}}$$

Single-pass inactivation rate (η)

$$\eta = 1 - S$$

D_{UV} = UV Dose (μJ/cm²) = $I \times t$

k = Pathogen-dependent inactivation rate constant (cm²/μJ)

I = Average irradiance (μW/cm²)

t = Exposure time (s)

The *2019 Handbook* also recommends that these systems be installed in a location that can provide a minimum of 0.25 s of UV exposure to minimize system cost and power consumption (~2 ft [~610 mm] length in the example above).[27] Reflective materials, like aluminum, can boost the intensity field from direct reflections (as well as interreflections) and increase the effective UV dose.[27,28] When the UV-C lamps have to be located in the ductwork (due to space constrictions, etc.), the effects of interreflections are often used. When the surface reflectivity is high and the volume is enclosed, the reflections can bounce between the surfaces and significantly contribute to the total field.[28]

Conclusions

Part 3 has looked at several common mitigation strategies and their application. Lack of proper ventilation has been shown to increase the chance of infections. Increasing ventilation above the minimum ventilation required by code has the ability to decrease particle concentrations in the space; however, a limit may exist to how much increased ventilation will decrease the infection risk. Distance from the contaminant source, direction of cough and quanta generation rate can decrease the effect that ventilation has on the infection rate. Filtration and UVGI are two common ways to increase a system's ventilation rate without bringing in additional outdoor air. Part 4 will briefly look at emerging technology and additional methods for virus mitigation.

References

1. Janssen, J. 1999. "The first century of air conditioning. Article 11: The history of ventilation and temperature control." *ASHRAE Journal* 41(10).

2. ANSI/ASHRAE Standard 62.1-2019, *Ventilation for Acceptable Indoor Air Quality*.

3. Burkett, J. 2021. "Virus transmission modes and mitigation strategies, part 1: Defining viruses and droplet release." *ASHRAE Journal* (3):24–29.

4. Qian, H., X. Zheng. 2018. "Ventilation control for airborne transmission of human exhaled bio-aerosols in buildings." *Journal of Thoracic Disease* 10(Suppl 19):S2295–S2304. https://doi.org/10.21037/jtd.2018.01.24

5. Atkinson, J., Y. Chartier, C.L. Pessoa-Silva, P. Jensen, et al., Eds. 2009. *Natural Ventilation for Infection Control in Health-Care Settings*. World Health Organization.

6. Li, Y., G.M. Leung, J.W. Tang, X. Yang, et al. 2007. "Role of ventilation in airborne transmission of infectious agents in the built environment—a multidisciplinary systematic review." *Indoor Air* 17(1):2–18. https://doi.org/10.1111/j.1600-0668.2006.00445.x

7. Sehulster, L., R. Chinn, M. Arduino, J. Carpenter, et al. 2004. "Guidelines for Environmental Infection Control in Health-Care Facilities: Recommendations from CDC and the Healthcare Infection Control Practices Advisory Committee (HICPAC)." American Society for Healthcare Engineering/American Hospital Association.

8. Brickner, P.W., R.L. Vincent, M. First, E. Nardell, et al. 2003. "The application of ultraviolet germicidal irradiation to control transmission of airborne disease: bioterrorism countermeasure." *Public Health Reports* 118(2):99–114. https://doi.org/10.1093/phr/118.2.99

9. ASHRAE. 2021. "Building Readiness." ASHRAE Epidemic Task Force. https://tinyurl.com/899sfp7s

10. Memarzadeh, F., W. Xu. 2012. "Role of air changes per hour (ach) in possible transmission of airborne infections." *Build. Simul.* 5:15–28. https://doi.org/10.1007/s12273-011-0053-4

11. Bolashikov, Z.D., A.K. Melikov, M. Brand, W. Kierat, Z. Popioek. 2012. "Exposure of health care workers and occupants to coughed airborne pathogens in a double-bed hospital patient room with overhead mixing ventilation." *HVAC&R Research* 18(4):602–615. https://tinyurl.com/4k3udnwd

12. Olmedo, I., P.V. Nielsen, M. Ruiz de Adana, R.L. Jensen, P. Grzelecki. 2012. "Distribution of exhaled contaminants and personal exposure in a room using three different air distribution strategies." *Indoor Air* 22(1):64–76. https://doi.org/10.1111/j.1600-0668.2011.00736.x

13. Nardell, E.A., J. Keegan, S.A. Cheney, S.C. Etkind. 1991. "Airborne infection: Theoretical limits of protection achievable by building ventilation." *American Review of Respiratory Disease* 144(2):302–306. https://doi.org/10.1164/ajrccm/144.2.302

14. Azimi, P., B. Stephens. 2013. "HVAC filtration for controlling infectious airborne disease transmission in indoor environments: Predicting risk reductions and operational costs." *Building and Environment* 70:150–160. https://doi.org/10.1016/j.buildenv.2013.08.025

15. Liao, C.M., S.C. Chen, C.F. Chang. 2008. "Modelling respiratory infection control measure effects." *Epidemiology and Infection* 136(3):299–308. https://doi.org/10.1017/S0950268807008631

16. *2020 ASHRAE Handbook—HVAC Systems and Equipment*.

17. Perry, J.L., J. Agui, R. Vijayakimar. 2016. "Submicron and Nanoparticulate Matter Removal by HEPA-Rated Media Filters and Packed Beds of Granular Materials." National Aeronautics and Space Administration. Report M-1414, NASA/TM-2016-218224. https://ntrs.nasa.gov/citations/20170005166

18. First, M.W. 1998. "Hepa filters." *Applied Biosafety* 3(1):33–42. https://doi.org/10.1177/109135059800300111

19. DOE. 2003. "DOE Handbook: Nuclear Air Cleaning Handbook." DOE-HDBK-1169-2003. U.S. Department of Energy. https://tinyurl.com/dsvyxw2k

20. ASHRAE Standard 52.2-2017, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*.

21. Zhang, J., D. Huntley, A. Fox, B. Gerhardt, et al. 2020. "Study of viral filtration performance of residential HVAC filters." *ASHRAE Journal* 62(8).

22. Mousavi, E.S., N. Kananizadeh, R.A. Martinello, J.D. Sherman. 2021. "COVID-19 outbreak and hospital air quality: A systematic review of evidence on air filtration and recirculation." *Environmental Science & Technology* 55(7):4134–4147. https://doi.org/10.1021/acs.est.0c03247

23. Bohanon, H., M. Zaatari. 2020. "Effect of ventilation and filtration on viral infection in residences." *ASHRAE Journal* 62(12):38–45.

24. Owen, K., C. Kerr. 2020. "What you can and can't do with ASHRAE Standard 52.2." *ASHRAE Journal* 62(12).

25. Ward, M., J.A. Siegel. 2005. "Modeling filter bypass: Impact on filter efficiency." *ASHRAE Transactions* 111(1):1091–1100.

26. Reed N.G. 2010. "The history of ultraviolet germicidal irradiation for air disinfection." *Public Health Reports* 125(1):15–27. https://doi.org/10.1177/003335491012500105

27. *2019 ASHRAE Handbook—HVAC Applications*.

28. Kowalski, W. J., W.P. Bahnfleth. 2000. "Effective UVGI system design through improved modeling." *ASHRAE Transactions* 106. ■