UVGI Design Basics

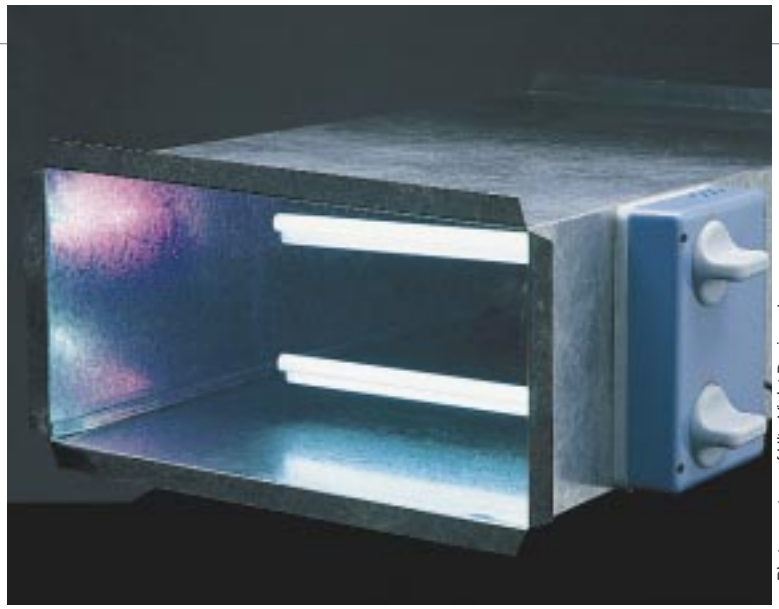

Photo courtesy of UltraViolet Devices, Inc.

for Air and Surface Disinfection

Ultraviolet germicidal irradiation lamps can help clean coils and improve indoor air quality

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Lethal to microorganisms, ultraviolet radiation in the range of 2250 to 3020 angstroms is used in a variety of disinfection applications, a process referred to as ultraviolet germicidal irradiation (UVGI).

Since the first UVGI system was successfully implemented for disinfecting the municipal water system in Marseilles, France,[1] in 1909, the disinfection of medical equipment using UVGI has been a common and reliable practice. But unlike water- and equipment-disinfection applications, the disinfection of air streams using UVGI has a history of varying success and unpredictable performance.

The first laboratory studies on UVGI of air in the 1920s showed such promise that the elimination of airborne disease seemed possible. In 1936, Hart used UVGI to sterilize air in a surgical operating room.[2] In 1937, the first application of UVGI for a school ventilation system dramatically reduced the incidence of measles, with subsequent applications enjoying similar success.[3] Experiments by Riley and O'Grady[4] resulted in the elimination of tuberculosis (TB) bacilli from hospital-ward exhaust air.

A plethora of designs that were more imitative than engineered followed these early applications. The result was a mixture of successes and failures. This experience is reflected in various guidelines that decline to sanction the use of UVGI as a primary system. A 1954 study on the use of UVGI showed a failure to reduce disease in London schools. Although limited data are available to determine the causes of earlier design failures, the apparent cloning of UVGI systems without regard to operating conditions probably doomed many installations from the start.

A review of current industry practices indicates that information on the design of UVGI systems lacks the detail necessary for engineers to ensure performance. This article addresses the factors that determine the design

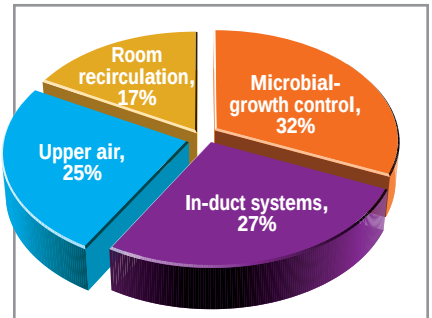

FIGURE 1. Types of UVGI systems and approximate share of market.

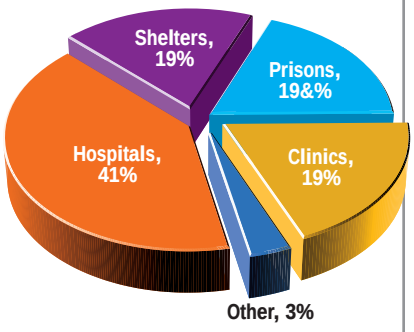

FIGURE 2. Approximate breakdown of where UVGI air-disinfection systems are being installed.

**William P. Bahnfleth is a member of HPAC Engineering's Editorial Advisory Board.*

[1]*Superscript numerals indicate references listed at end of article.*

parameters of UVGI systems and discuss methods that can be used to size systems more effectively.

TYPES OF UVGI SYSTEMS

Figure 1 shows the types of UVGI systems that are sold for building-air and air-handling-unit (AHU) applications and their approximate share of the market, based on estimates from a number of major manufacturers. The use of systems for disinfecting air and controlling microbial growth is growing in the United States and Europe, according to manufacturers. In the Third World, however, demand for upper-air-disinfection systems is high because of the TB pandemic, strained economics, and the common use of natural ventilation.

As shown in Figure 2, health-care facilities are where the most UVGI systems are installed. Notably absent are schools, office buildings, and public and residential buildings, even though these are major sources of contagious respiratory diseases.

AIR-STREAM-DISINFECTION APPLICATIONS

The first step in the design of an air-stream- or surface-disinfection system is to characterize the application. This includes describing the air stream, identifying the specific surface, and, sometimes, targeting specific microbes, such as TB.

UVGI units commonly are located in an AHU downstream from the mixing box. Photo A shows a typical air-stream-disinfection system installed downstream from the filter bank and upstream from the cooling coils.

PHOTO A. UVGI array used for air disinfection. Note the specular reflective surfaces. Photo courtesy of Lumalier Inc., Memphis.

Photo courtesy of Airguard Industries Inc., Louisville.

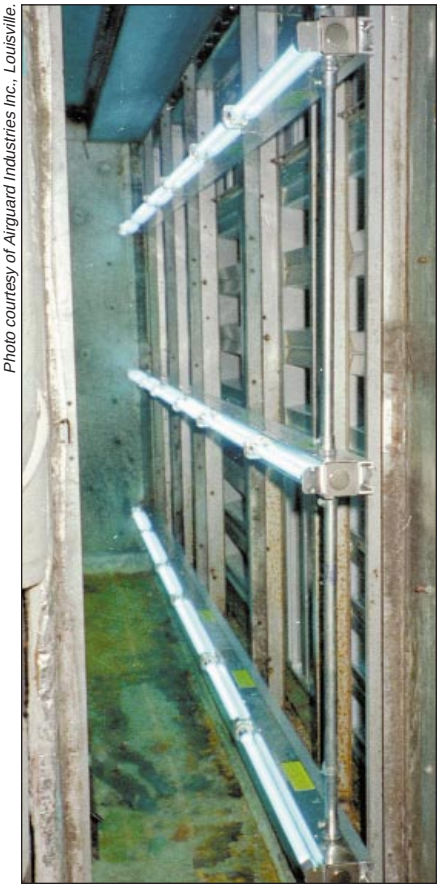

PHOTO B. UVGI lamp array used to disinfect a filter bank. The filters are to the left.

Although UVGI systems also can be placed in a return-air duct to deal with recirculated, contagious pathogens, they are rarely placed in outside-air-supply ducts. Spores, which hail from the outdoors, are more efficiently removed by filtration alone. An exception exists in cases such as AIDS clinics, where environmental bacteria from the outdoors could threaten immunodeficient patients indoors.

SURFACE-DISINFECTION APPLICATIONS

UVGI for microbial-growth control has been undergoing much study recently and has enjoyed success in field applications.[5,6] Microbial growth may be comprised of fungi, bacteria, or even algae, but never viruses. In Europe, microbial-growth control on cooling coils has been practiced in breweries since at least 1985. One manufacturer recommends placing a 15-W lamp 1 m from the surface of cooling coils or walls where condensation may occur.[7]

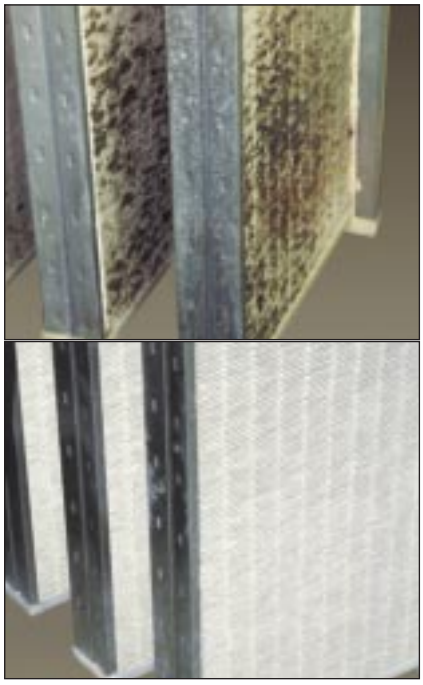

PHOTO C (top): Microbial growth on unirradiated filters. PHOTO D (bottom): Microbe-free irradiated filters.

Direct UVGI exposure can sterilize any surface if given enough time. Theoretically, low-intensity UVGI could be used for microbial growth because the exposure time is extended. In practical applications, however, microbial growth can occur in crevices, shadowed areas such as insulation, and stagnant water where UVGI may not completely penetrate.

UVGI can control microbial growth on filters subject to moisture or high humidity. Photo B shows a test application of UVGI for controlling microbial growth on filters. Photos C and D show an unirradiated and irradiated filter bank, respectively. The unirradiated filters show natural contamination from various fungal species, including *Aspergillus* and *Penicillium*, while the irradiated filters show no evidence of microbial growth. The system in photos B, C, and D used lamps that produce a rated intensity of 100 $\mu W/cm^2$ at 1 m from their midpoints.

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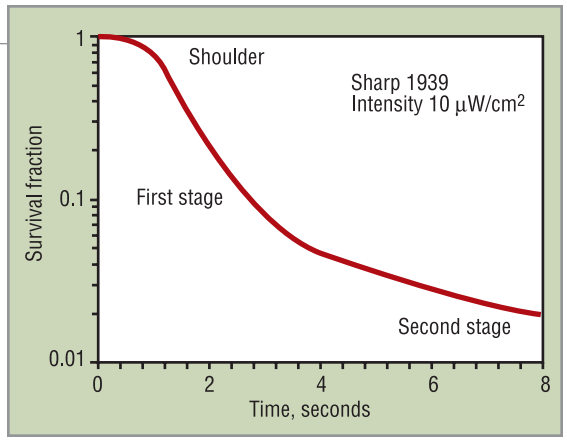

FIGURE 3. Survival curve for Staphylococcus aureus *illustrating the shoulder portion and two distinct stages of decay. (Source: Sharp, G. 1940. The effects of ultraviolet light on bacteria suspended in air. J. Bact. 38:535-547.)*

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TYPES OF MICROORGANISMS

The variety of microbes encountered by a given UVGI system is essentially unpredictable. It depends to some degree on the type of facility and geographic location.

All viruses and almost all bacteria (excluding spores) are vulnerable to moderate levels of UVGI exposure. Because viruses are primarily contagious pathogens that come from human sources, they are found in occupied buildings. Bacteria can be contagious or opportunistic, with many found indoors; however, some are environmental. Certain facilities, such as agricultural buildings, may disseminate unique types of bacteria, such as spore-forming actinomycetes.

Spores, which are larger and more resistant to UVGI than most bacteria, can be controlled effectively through the use of high-efficiency filters. The coupling of filters with UVGI is the recommended practice in all healthcare settings[8] and for UVGI applications in general.

MICROBIAL RESPONSE TO UVGI

A basic review of the mathematics of UVGI disinfection will assist design engineers. The population S of a species exposed to any biocidal factor is described by the characteristic logarithmic decay equation:

$$S(t) = e^{-kIt} \qquad (1)$$

where:

k = standard decay-rate constant, $cm^2/\mu W - s$

I = intensity of UVGI irradiation, $\mu W/cm^2$

t = time of exposure (sec)

The standard decay-rate constant defines the sensitivity of a microorganism to UVGI and is unique to each microbial species.[9] It can be thought of as the rate constant at an intensity of 1 $\mu W/cm^2$, providing a basis for comparing pathogens. The rate constant for *E. coli*, commonly used for design purposes, is 0.000767 cm^2 per μW sec.

Equation 1 omits two characteristics that may impact the disinfection pro-

cess: the shoulder and the second stage. The shoulder represents the delay in response (or threshold dose) of a microorganism subject to UVGI exposure. If air velocity is too high and the dose is insufficient, a microbe may have a negligible response or even recover from the damage. Insufficient data exists to determine the shoulders, or threshold doses, of most airborne pathogens.

Most microbial populations exhibit characteristic two-stage inactivation curves (Figure 3) in which each stage has a unique rate constant. The total survival curve is the sum of a fast-decay curve (the vulnerable majority) and a slow-decay curve (the resistant minority), as follows:

$$S(t) = Fe^{-k_f It} + (1-F)e^{-k_s It} \qquad (2)$$

where:

k_f = rate constant for fast-decay population

k_s = rate constant for slow-decay population

F = fraction of the total initial population subject to fast-decay response

The resistant fraction of most microbial populations is about 0.01 percent, although some studies suggest that it can be as high as 10 percent for certain species.[3]

A distinction exists between the terms "disinfection" and "sterilization." Sterilization is defined as the complete destruction of all microbial species. Sterilization sometimes is considered to be 99.9999-percent eradication, or a six-log (base-10) reduction in microbial population. Disinfection, on the other hand, is merely the reduction of microbial population. Because air streams are generally disinfected, not sterilized, this residual second stage usually can be ignored.

DESIGN PARAMETERS

A number of parameters must be considered when considering UVGI products for HVAC designs. The most important factors are the air-flow or HVAC equipment that will be disinfected, the lamp wattage and distance, and the ventilation system design itself.

Air-stream characteristics

The characteristics of an air stream that can impact UVGI design are relative humidity (RH), temperature, and air velocity.

Increased RH is commonly believed to decrease decay rates under ultraviolet (UV) exposure. However, studies on this matter are contradictory and incomplete at present. Fortunately, because most UVGI studies have been conducted under normal indoor conditions, typical room and in-duct applications are not likely to differ greatly.

Air temperature has a negligible impact on microbial susceptibility to UVGI.[10] However, it can impact the power output of UVGI lamps if it exceeds design values.

Operating a UVGI system at air velocities above design will degrade the system's effectiveness because of the cooling effect of the air on the lamp surface, which, in turn, will cool the plasma inside of the lamp. UV output

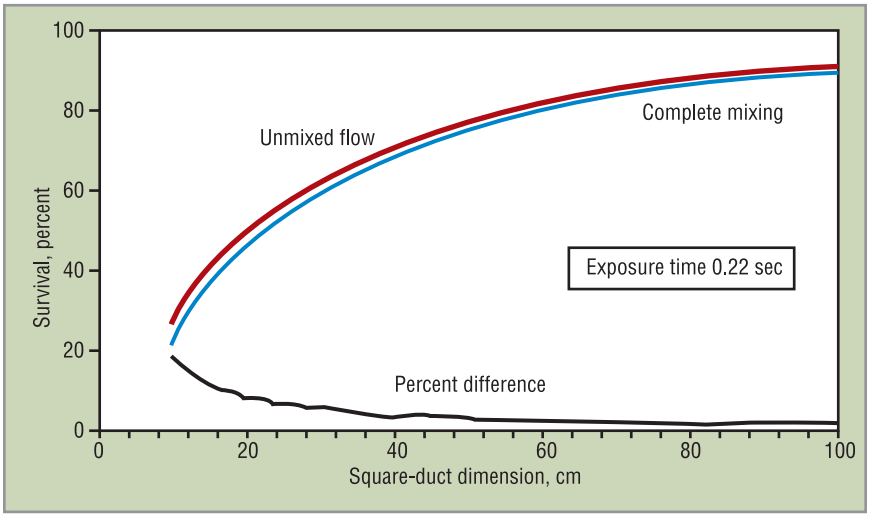

FIGURE 4. Survival of E. coli *under mixed flow and unmixed flow in square ducts of increasing dimension.*

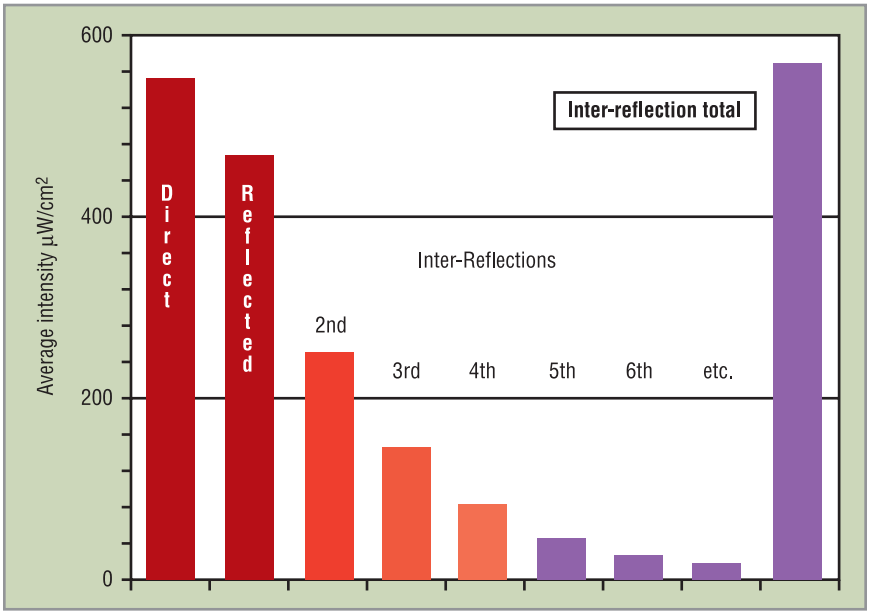

FIGURE 5. Calculated additional light intensity from reflections and inter-reflections. Total intensity is the sum of direct, reflected, and inter-reflected UV light.

is a function of plasma temperature when power input is constant.

Not all UVGI lamps have the same response to cooling effects. Some lamps have different plasma mixtures; overdriven power supplies that respond to plasma temperature; or UV-transparent, infrared-blocking shielding that limits cooling effects. Data from the manufacturer should be consulted to determine the cooling effects or the limiting design air velocities and temperatures within which the lamps can be operated efficiently.

Ventilation system design

A number of ventilation system parameters can impact UVGI design.

Air velocity and air mixing. Doses are determined by the time of exposure and UVGI intensity, both of which are dependent on the velocity profile and the amount of air mixing in the air stream. The velocity profile inside of the duct or chamber depends on local conditions and may be impossible to know in advance with any certainty. In any event, the design velocity of a typical UVGI unit is similar to that for filter banks—about 400 fpm. Sufficient mixing will occur at these velocities to temper the effects of a non-uniform velocity profile.

The amount of air mixing that occurs will affect system performance to a degree that depends on system configuration. This is illustrated in Figure 4, which compares survival predictions for mixed- and unmixed-flow conditions in square ducts of increasing dimension. The error resulting from the assumption of complete mixing will decrease as system dimensions increase.

In systems in which the lamps do not span the duct's entire width or length, the assumption of complete mixing also will result in larger differences, compared to unmixed flow. The important point is that system operation will lie somewhere between these two assumptions, which provide limits describing system efficiency.

Using reflectors. Reflectivity can be an economical way of intensifying the UVGI field in an enclosed duct or chamber. A surface with a reflectivity of 90 percent will reflect ⅞ of the light it receives.

The results of a computer-generated analysis of reflectivity are shown in Figure 5. The components of reflectivity—both direct and inter-reflected—will clearly sum to greater than the initial direct intensity. This can occur whenever the surface is mostly enclosed and highly reflective. Such designs can considerably improve economics.

Two types of reflective surfaces exist: specular and diffuse. Specular surfaces produce mirror-like reflections that are directionally dependent on the source, while diffuse surfaces produce non-directional reflections that

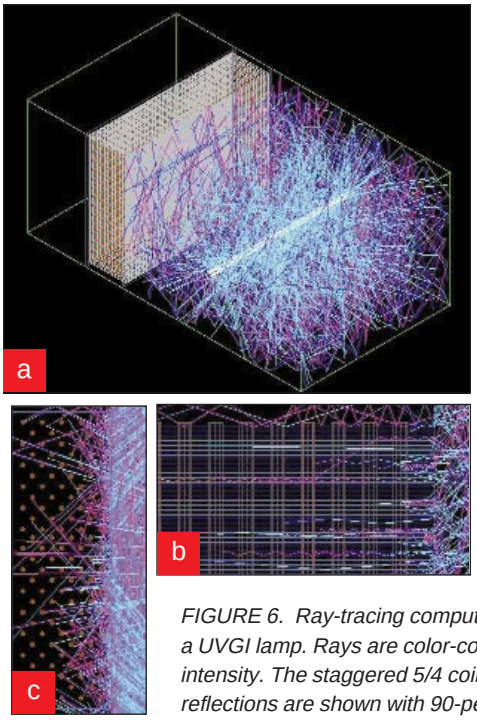

FIGURE 6. Ray-tracing computer model of a cooling-coil bank irradiated with a UVGI lamp. Rays are color-coded from blue to red in order of decreasing intensity. The staggered 5/4 coil tubes are 0.5-in. dia. with six fins per in. Five reflections are shown with 90-percent reflective duct surfaces. Perspectives are (a) isometric, (b) front, and (c) side.

spread equally in all directions. Nonglossy white paper is a good example of a diffuse surface. Most materials possess a combination of specular and diffuse properties and exhibit a degree of directional dependence. For UVGI design purposes, the degree of directional dependence is usually not critical.

Some materials reflect visible light, but not UV light. Polished aluminum is highly reflective to UV wavelengths, while copper, which reflects most visible light, is transparent in the UV range.

No simple method of calculating the three-dimensional UVGI-intensity field for specular reflectors exists. Ray-tracing routines using Monte Carlo techniques are one approach, but the results do not easily lend themselves to analysis. However, they can be rather useful for examining complex geometries, such as when cooling coils are irradiated. Figure 6 shows ray-tracing diagrams of a UVGI lamp irradiating a bank of cooling coils from three perspectives. Note how few of the rays penetrate the coils, even after 20 reflections. Also note how the copper tubes absorb many of the rays—although copper is transparent to UVGI, the water inside is not.

Combining with filtration. UVGI systems generally are used in combination with HEPA filters, a practice usually recommended for isolation-room applications. For other applications, however, HEPA filters do not offer a significant enough improvement in microbe-removal rates over high-efficiency filters to warrant their exclusive use with UVGI.

Recirculation systems. UVGI systems that recirculate room air or that are placed in a return-air duct or mixing-air plenum deliver multiple doses to airborne microorganisms. Although the effect is partially dependent on the air-change rate, the result is an effective increase in removal rate in comparison with a single-pass system.

Calculations of removal rates for UVGI and associated filters in recirculation systems can be performed by evaluating the system minute-by-minute, including filtration rates, outside-air rates, and any microbial contaminants.

Lamp considerations

The hardest part of sizing a UVGI system is determining the lamp wattage for the stated disinfection goal. The intensity field caused by the lamp and the reflectors must be modeled and averaged before Equation 1 is used to predict the disinfection rate.

Calculating the Intensity Field of a UVGI Lamp

The intensity field of a UVGI lamp can be computed using the following radiation view factor from a differential planar element to a cylinder, perpendicular to the cylinder axis (Modest, M.F. 1993. Radiative Heat Transfer. McGraw-Hill, New York.):

$$F_{d1-2} = \frac{1}{\pi H} ATAN\left(\frac{L}{\sqrt{H^2-1}}\right) + \frac{X-2H}{\sqrt{XY}} ATAN\left(\sqrt{\frac{X(H-1)}{Y(H+1)}}\right)\frac{L}{\pi H} - ATAN\left(\sqrt{\frac{H-1}{H+1}}\right)\frac{L}{\pi H}$$

The parameters in the equation at left are defined as follows:

H = x/r

L = l/r

$X = (1 + H)^2 + L^2$

$Y = (1 - H)^2 + L^2$

where:

l = length of the lamp segment, cm

x = distance from the lamp, cm

r = radius of the lamp, cm

The intensity at any point will be the product of the view factor and the surface intensity of the lamp. The surface intensity is simply the UV power output in watts divided by the surface area in cm^2.

To compute the intensity at any distance from the midpoint of a lamp, multiply the above equation by 2. From any location other than the midpoint, divide the lamp into two unequal segments and add the two view factors. View-factor algebra (see reference) can be used for other locations. If we assume that complete mixing occurs, then the intensity field for any duct can be computed by averaging the field in all three dimensions.

Width cm	Height cm	Airflow m^3/min	Lamp UV watts	Reflectivity percent	Kill rate, percent	
					Minimum	Maximum
100	50	60	12	50	45	48
				75	63	74
				90	**74**	**96**
100	50	60	24	50	69	72
				75	85	93
				90	**92**	**99**
100	50	60	36	50	81	86
				75	93	98
				90	**97**	**99**
100	100	120	36	50	61	64
				75	72	76
				90	**79**	**83**
100	100	120	48	50	70	75
				75	81	85
				90	**87**	**91**
100	100	120	56	50	75	80
				75	85	89
				90	**90**	**94**
200	200	480	96	50	47	59
				75	56	68
				90	**62**	**73**
200	200	480	144	50	58	74
				75	68	82
				90	**74**	**86**
Travel time = 0.5 sec; lamp length = 72 cm; radius = 1.9 cm						

TABLE 1. Predicted disinfection rates for typical systems.

Lamp-intensity field. An exact description of the lamp-intensity field is necessary to accurately determine the dose that is to be delivered to an airborne microorganism. Lamp ratings often are the sole parameter used for sizing a UVGI installation. Although this may be a conservative approach when distances to the lamp exceed 1 meter, oversizing and prohibitive economics can result.

If complete mixing is assumed, then any intensity field can be described by the single value of average intensity. This requires computing the intensity at every point in a three-dimensional matrix defining the duct. We need to know the field caused by the lamp and, if necessary, the field caused by the reflections. Although the inverse-square law has been used for this purpose, it has proven to be inaccurate close to the lamp. An improved approach is to use the radiation view factor from a differential planar element to a cylinder as detailed in the sidebar *Calculating the Intensity Field of a UVGI Lamp*. Ignoring reflectivity, the average intensity field can be conservatively computed by applying Equation 3 to a three-dimensional matrix.

There are view factors that can be used for computing the reflected intensity from flat parallel or perpendicular surfaces. Consult any thermal-radiation textbook for such view factors.

UVGI Economics

Table 2 summarizes the costs associated with purchasing, installing, and operating two types of UVGI systems: an air-stream-disinfection (AD) system and a microbial-growth-control (MGC) system. The ventilation systems for both are identical. These systems were sized using the techniques described in the accompanying article, with predicted disinfection rates as shown.

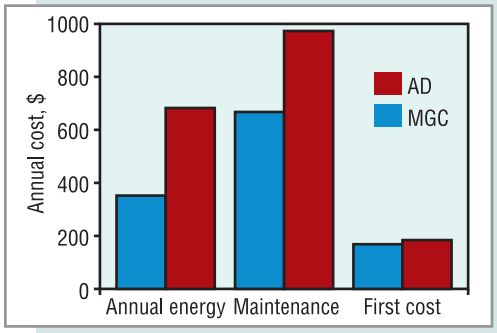

FIGURE 7. A comparison of UVGI air-stream-disinfection (AD) and microbial-growth-control (MGC) systems for a 20-year life cycle.

The location used in the energy analysis is Philadelphia, with the heat added by the lamps resulting in a cooling energy penalty for 30 percent of the year. No credit is taken for energy input during the heating season. Clearly, the first cost of each of these systems is minor, with the maintenance cost eclipsing the energy cost.

Although the MGC system uses less wattage, it operates continuously, while the AD system operates only when the building is occupied. The power requirements of the former system are appropriate for disinfection of duct surfaces or filter faces, but not necessarily for cooling costs.

A critical energy difference between these systems occurs because the AD system has an ASHRAE 25-percent filter, while the MGC system has a dust filter only. Because the short exposure time in an AD system may not effectively reduce spore levels, it becomes cost-effective to use a higher-efficiency filter to control spores. The MGC system renders spores inactive with continuous (24-hr) exposure and, as a result, needs only a dust filter for purposes of cleanliness.

Type of UVGI Application	Airstream disinfection		Microbial-growth control	
Design airflow	10,000	cfm	10,000	cfm
	283	m^3/min	283	m^3/min
Velocity	413	fpm	413	fpm
	2.10	m/s	2.10	m/s
Predicted disinfection	90	Percent E. coli	99.99	Percent *Aspergillus*
Number of lamps	2		1	
Height	150	cm	150	cm
Width	150	cm	150	cm
Length	400	cm	—	NA
Face area	22,500	cm^2	22,500	cm^2
Exposure time	1.91	sec	Continuous	sec
Total power	36	W	16.1	W
UV Power	12.7	W	3.2	W
Power dropoff at end of life	30	percent	15	percent
Average UV power over life	10.795	W	2.96	W
Diameter	1.4351	cm	1.6	cm
Length	77.47	cm	28.83	cm
Total power draw	0.072	kw	0.0161	kw
Hours of operation				
(12 hours x 6 days x 52 weeks)	3744	hours	8760	hours
Total power	270	kw-hr	141	kw-hr
Efficiency breakdown				
Heat generated	0.0466	kw	0.0129	kw
Heat generated	159	Btu/hr	44	Btu/hr
Cooling load	595,642	Btu	385,796	Btu
Cooling load (75 percent of year)	131	kw-hr	85	kw-hr
System pressure losses				
Side area	111.1772	cm^2	46.128	cm^2
Total area	222.35439	cm^2	46.128	cm^2
Framing/fittings	44.4708788	cm^2	9.2256	cm^2
Total area	266.82527	cm^2	55.3536	cm^2
Free-area ratio	0.9881		0.9975	
Loss coefficient				
(ASHRAE CR6-1)	0.0014		0.00018	
Press loss (lamps and fixtures)	1.468E-05	in.w.g.	1.887E-06	in.w.g.
Filter dP (average/lifetime)	0.56	in.w.g.	0.29	in.w.g.
Air HP	0.982	hp	0.508	hp
Fan-motor HP				
(80-percent Eff. total)	1.2271322	hp	0.6354666	hp
Energy cost	0.9150725	kw	0.4738675	kw
Total fan energy	3426	kw-hr	4151	kw-hr
Energy-cost summary				
Electrical energy	270	kw-hr	141	kw-hr
Cooling energy	131	kw-hr	85	kw-hr
Fan energy	3426	kw-hr	4151	kw-hr
Total energy	3826	kw-hr	4377	kw-hr
Rate	0.08	$/kw-hr	0.08	$/kw-hr
Annual cost	**306**	$	**350**	$
Replacement cost				
Average tube life	10,000	hr	10,000	hr
Tube hours/year	7488	hr	8760	hr
Replacements/year	0.75		0.88	
Cost/tube	85	$	85	$
Number of filters	4		4	
Filter type	25 percent		Pre	
Filter replacements/year	3		3	
Cost/filter (assumed)	10	$	2	$
Annual cost	94	$	80	$
Maintenance (assumed)	400	$	400	$
Annual cost	**800**	$	**831**	$
First costs				
UVGI lamps and fixtures				
(AU prices)	465	$	250	$
Reflective aluminum surfaces				
(assumed)	300	$	0	$
Labor (est. per means)	10,000	$	6000	$
Total installation cost	10,765	$	6,250	$
Life cycle	20	years	20	years
Interest rate	8	percent	8	percent
Capital recovery factor	0.1018522		0.1018522	
Life-cycle cost	**1096**	$	**637**	$
Total annual cost	**2202**	**$**	**1817**	**$**

TABLE 2. Economic evaluation of typical UVGI systems.

First, use Equation 3 to determine the intensity at the flat surface. Then, use the appropriate view factor to determine the reflected intensity after multiplying by the reflectivity.

Table 1 presents a comparison of UVGI systems that were sized using the view-factor method and may be used to approximate the performance of similar systems.

CONCLUSIONS

Although simplistic, the methodology presented here is more accurate than any previously published method for sizing UVGI systems. The authors hope that these principles will lead to successful applications and avoidance of the design problems that have hampered the industry and perplexed engineers. Although the goal of eliminating airborne disease might remain unachievable, the information presented here may help lead the industry back to the path of continuous improvement.

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REFERENCES

1) AWWA. 1971. Water Quality and Treatment. McGraw-Hill, New York.

2) Sharp, G. 1939. The lethal action of short ultraviolet rays on several common pathogenic bacteria. J. Bact. 37:447-459.

3) Riley, R.L. 1972. The ecology of indoor atmospheres: Airborne infection in hospitals. J. Chron. Dis. 25:421-423.

4) Riley, R.L., and F. O'Grady. 1961. Airborne Infection. The Macmillan Co., New York.

5) Shaughnessy, R., E. Levetin, and C. Rogers. 1999. The effects of UV-C on biological contamination of AHUs in a commercial office building: Preliminary results. Indoor Environment '99:195-202.

6) Scheir, R., and F.B. Fencl. 1996. Using UVC Technology to Enhance IAQ. *Heating/Piping/Air Conditioning.* February 1990.

7) Philips. 1985. UVGI Catalog and Design Guide, Catalog No. U.D.C. 628.9, Netherlands.

8) ASHRAE. 1991. Health Facilities. ASHRAE (ed.), ASHRAE Handbook of Appl., Atlanta.

9) Jensen, M.M. 1964. Inactivation of airborne viruses by ultraviolet irradiation. Appl. Microb. 12(5):418-420.

10) Rentschler, H.C., R. Nagy, and G. Mouromseff. 1941. Bactericidal effect of ultraviolet radiation. J. Bact. 42:745-774.