CH-99-12-2

Guidelines for the Application of Upper-Room Ultraviolet Germicidal Irradiation for Preventing Transmission of Airborne Contagion—Part II: Design and Operation Guidance

Melvin W. First, Sc.D., P.E. **Edward A. Nardell, M.D.**

William Chaisson, P.E. **Richard Riley, M.D.**
Life Member ASHRAE

ABSTRACT

Installations of ultraviolet germicidal irradiation (UVGI) have been stimulated recently by a sudden rise in the incidence of tuberculosis. Hospitals, jails, and homeless shelters have been the most frequently equipped facilities because they are places where many tuberculosis cases are found, the buildings housing them tend to be old and not suited for economical increases in air exchange rates, and the work staffs have been apprehensive about transmission to themselves and their families. The diversity in structures currently being equipped with UVGI installations, plus the introduction of new designs of lamps and fixtures, have made it clear that an updated review of equipment performance factors and practical installation guidelines will be useful to interested parties. Illustrative examples are given of installations that have been made in a diverse set of facilities. In addition, representative figures are given to compare the cost of HVAC installations and UVGI installations that give an equivalent number of air changes based on equal levels of reduction in airborne microorganisms.

INTRODUCTION

Satisfactory installations of upper-room ultraviolet germicidal irradiation (UVGI) equipment intended to reduce transmission of infectious airborne microorganisms depend on a correct selection of appliances (number, design, and UV power output to fit the geometry and area of the space) and careful attention to their location (for maximum efficacy and to avoid eye irradiation). After this has been accomplished, it is only necessary to perform simple, routine maintenance procedures to keep the equipment operating in the design mode.

Although there is ample published material on the quantitative effects of graduated doses of ultraviolet germicidal radiation on the destruction of a wide spectrum of microorganisms in water, air, and on surfaces (see Part I, First et al. 1999), there is less information available on how to use this technology productively in the widely diverse situations encountered in practical applications at facilities such as hospitals, jails, homeless shelters, sports arenas, transportation terminals, and theaters. Much that is currently understood about application engineering has been acquired by trial-and-error methods and translated into rules of thumb. For this reason, it is considered important to assemble the rules of good engineering practice to make the information generally available and to allow it to be subjected to critical examination for confirmation or correction.

It has become common practice to express UVGI effectiveness in terms of equivalent room air changes added to the existing ventilation rate, but there is little information on what this means in terms of costs avoided had the choice been made to add the indicated room air changes by HVAC methods instead. Cost figures for two recent large UVGI installations have been made available to us, and they have been compared with representative costs to install and operate the amount of added HVAC that would be needed to realize the same reduction in the number of airborne M. tuberculosis bacteria. Although the cost figures used are real and current, comparisons are based on certain stated assumptions that may not be appropriate for all applications. Because a meaningful

Melvin W. First is professor emeritus of environmental health engineering, Harvard School of Public Health, Harvard University, Boston, Mass. **Edward A. Nardell** is associate professor of medicine, Harvard Medical School, Cambridge, Mass. **William Chaisson** is a consultant with Chaisson Consultants, Newton, Mass. **Richard Riley** is professor emeritus at Johns Hopkins University, Petersham, Mass.

BACK TO PAGE ONE

comparison must deal with the realities associated with each specific application, the values given here should be viewed as illustrative.

PERFORMANCE OF ULTRAVIOLET GERMICIDAL LAMPS AND FIXTURES

Lamp manufacturers catalog their products by the number of watts of electricity required to make them function correctly; presumably this is done to guide circuit designers and installers to provide adequate electrical services. Users are more interested in lamp UV output, also expressed in watts, which, as noted in Part I, turns out to range from 25% to 33% of input power, depending on the particular lamp and transformer combination. This information is generally provided by the lamp manufacturer. When lamps are installed in fixtures, more particularly in upper-room types that feature enclosures with louvers, effective output irradiance is further reduced by a decrease in radiation emission openings as well as by reflector losses and losses to nonreflecting interior surfaces (Dumyahn and First, in press). This information should be provided by the fixture manufacturer. Effective output may be affected adversely by installation exigencies, whereas manufacturers' data represent ideal conditions.

As it is possible to identify the wattage of the same fixture by several different designations (lamp manufacturer's rating, lamp-transformer input, lamp output, and fixture output), one should carefully identity which "watt unit" is being cited, although in practice, it is seldom done. To avoid ambiguity, we will cite the power of fixtures in terms of the total lamp input power that they require, thereby simplifying the discussion by eliminating output differences associated with design and installation variations. The electrified load for the fixture will be the sum of the lamp input plus the ballast losses. For practical applications, these same variations can be important, and manufacturers' catalog data and advice should be sought and followed. Input wattages for the compact lamp design are 9 W and 18 W. For the tubular 36 in. lamp, 30 W is common, but it can vary depending on ballasts and lamp construction. Shorter tubes are rated for 4 W to 15 W. Some typical lamp sizes and their emission power are shown in Table 1, but lamps are available in a still wider range of types, sizes, and capacities. When partial baffling must be inserted in the emission path to shield a particular sector or spot from direct irradiation, the nominal fixture power rating should be reduced by the same fraction that the emission-port area is reduced. Changes in operating temperature are reported to affect emission strength, and total fixture output declines at a rate of 10% to 20% per year as lamps age. Hence, the practice of changing lamps annually. This occurs because the glass becomes less transparent to UV as it degenerates (solarizes) from the irradiation. Because lamps decline especially rapidly in emission power during the first 100 hours of operation, manufactures' output ratings refer to lamps after 100 hours of "burn-in." Emission power decline generally reaches steady state after about 1,000 hours.

TABLE 1
Typical Ultraviolet Germicidal Lamp Input and Output Wattages

Lamp Input	Tube Length	Lamp Output Wattage	
W	in.	W	Percent of Input
4 (tube)	5.5	0.5	12.5
6 (tube)	8.3	1.2	20
8 (tube)	11.4	1.8	22.5
15 (tube)	18	4	27
30 (tube)	36	10	33
36 (tube)	48	41	39
9 (compact)	8.3	2.5	28

At distances up to 3 m from louvered fixtures, 95% of the emission is confined to a 30 cm band height. The horizontal spread of radiation from louvered wall- and corner-mounted fixtures depends on the type and number of lamps and other design characteristics, such as open or closed sides. At all distances from a fixture, emission characteristics remain relatively continuous with some minor variation close in due to blockages caused by louver support rods and lamp orientation within the fixtures. Other factors affecting irradiance uniformity are reflections from walls, beams, and ceilings and shadows cast by furnishings. In large areas where several fixtures have been installed, overlap of emission coverage must also be considered. Although irradiance decreases from a point source as the square of the distance, the geometry of the lamps, the presence of collimating louvers, and the otherwise tight enclosure of the fixtures all alter this simple relationship. For distances up to 2 m to 3 m from the face of louvered fixtures, irradiance tends to fall off somewhat irregularly but more like the inverse of distance, gradually transforming to the inverse square rule.

Isoirradiance diagrams for the horizontal centerplane of a typical wall, corner, and pendant unit are shown in Figures 1 through 3. They show distance from the fixture at the indicated irradiance. At elevations above and below the horizontal centerplane, the irradiance is significantly more constricted, as shown in Figure 4. The horizontal isoirradiance diagram shown in Figure 1 is of a wall-mounted fixture equipped with a parabolic mirror and two compact 9 W lamps (2.5 W UV output). As the horizontal angle from the center of the fixture is increased, irradiance decreases at all distances from the centerline. Approximately one-fourth of a 12 ft × 12 ft room (4 m × 4 m), defined by the dashed lines in Figure 1, would experience horizontal centerplane intensities of 10 $\mu w/cm^2$ and higher, and most of the remainder of the room would be between 5 $\mu w/cm^2$ and 10 $\mu w/cm^2$. From Figure 4 it can be seen that the vertical irradiance gradient above and below the centerplane is rather steep; at 5 ft (1.5 m) out from the fixture along the vertical centerplane, the 10 $\mu w/cm^2$ isoirradiance line covers a band of only 10 in. (25 cm), and at 12 ft out (4 m), the 10 $\mu w/cm^2$ line is somewhat narrower. Figure 2 shows the

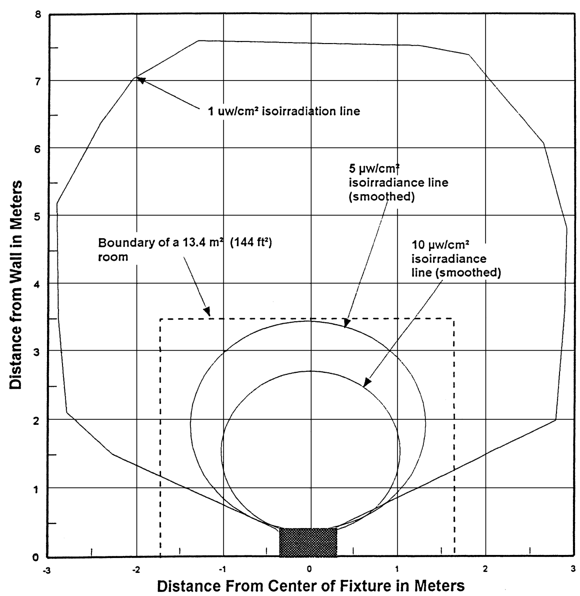

Figure 1 *Emission from a wall-mounted fixture with closed sides containing two 9 W lamps. (Dumyahn, in press.)*

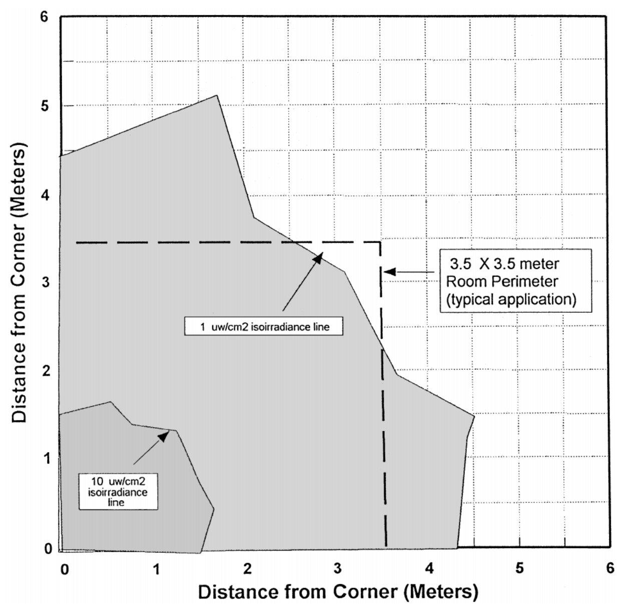

Figure 2 *Horizontal centerplane emission field of a typical corner-mounted fixture. (Dumyahn, in press.)*

horizontal centerplane emission field from a corner-mounted fixture equipped with two 9 W compact lamps and a flat reflector. The coverage area is constricted by the confining walls of the room. Irregularities in the isoirradiance lines are due to shadows made by louver supports. Corner-mounted units have special utility for spaces of unusual geometry or limited mounting choices.

Figure 3 is an isoirradiance plot for a typical cylindrical pendant fixture containing four 9 W compact lamps equally spaced around the vertical axis. Variations in irradiance due to the shadows of the vertical support rods and the orientation of

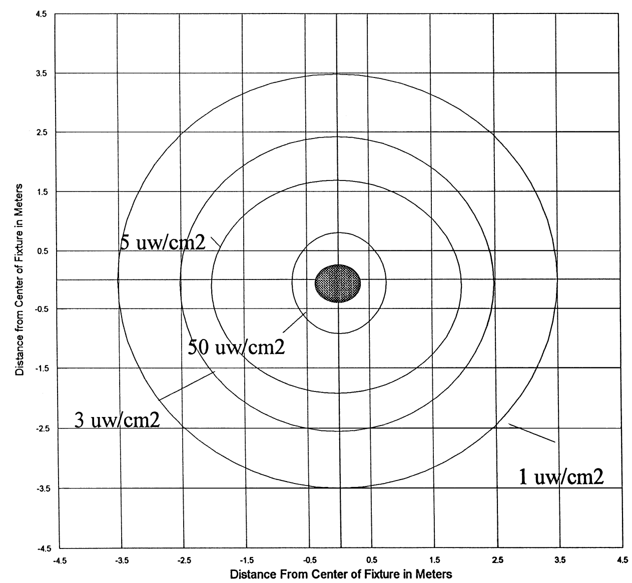

Figure 3 *Isoirradiance in the horizontal centerplane of a pendant (ceiling-mounted) UVGI fixture (Dumyahn, in press.)*

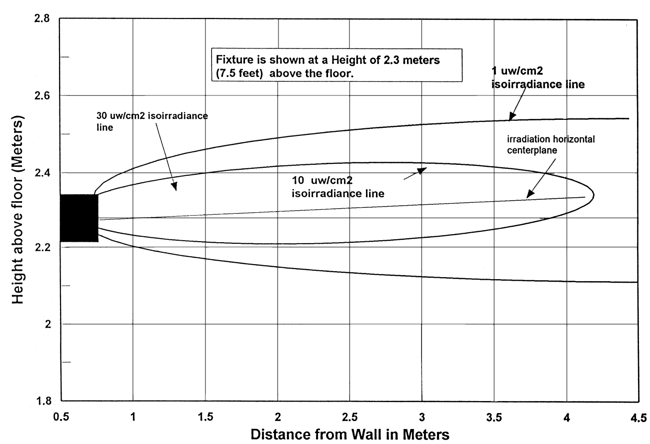

Figure 4 *Vertical irradiation profile for a 30 W fixture. (Dumyahn, in press.)*

the lamps have been smoothed to produce the circular isoirradiance lines. Because of these irregularities, isoirradiance measurements along only one radius may not adequately describe the total 360° emission from this type of fixture.

The maximum irradiance at increasing distances from a fixture in the horizontal centerplane can usually be derived from information provided in manufacturers' catalogs. However, as Figure 4 shows, the sharp falloff in irradiance in the vertical dimension of the emission zone of a typical wall-mounted fixture (shown in Figure 2a of Part I) confirms that there is much less vertical spread of the beam with distance. It also shows that the use of only horizontal centerplane irradiance measurements significantly overestimates the total radiation flux from a fixture. The restricted vertical spread of irradiance is similar for corner- and ceiling-mounted fixtures. Table 2 is a tabular representation of a typical radiation field

BACK TO PAGE ONE

TABLE 2
Irradiance Readings in μW/cm² for a Wall-Mounted UVGI Fixture Equipped with 8.5 W (Nominal Lamp Output) Longline Lamp (Dumyahn and First, in press)

Vertical Offset	Vertical Centerplane (Directly in Front of Fixture)			3.05 m Radius Lateral Offset	
	Distance from Rear of Fixture				
(cm)	1.52 m	3.04 m	4.57 m	@ 30°	@ 45°
45.7					
43.2					
40.6	0.33	0.28	0.26		
38.1	0.37	0.32	0.31		
35.6	0.42	0.36	0.37		
33.0	0.49	0.41	0.44		
30.5	0.57	0.5	0.55		
27.9	0.66	0.61	0.69		
25.4	0.80	0.76	0.89		
22.9	0.97	1.0	1.32		
20.3	1.24	1.39	2.02		
17.8	1.68	2.1	3.23		
15.2	2.45	3.79	4.94	1.09	0.37
12.7	4.19	7.1	6.95	2.17	0.66
10.2	11.81	12.94	8.95	4.23	1.54
7.6	36.4	20.2	10.78	8.15	3.55
5.1	72.9	26.3	12.05	12.65	6.67
2.5	100.2	29.6	12.97	15.83	8.92
0.0	100.7	29.9	12.97	17.30	10.02
–2.5	77.6	27.1	12.07	16.59	9.32
–5.1	44.4	21.5	10.76	16.48	8.97
–7.6	13.69	14.5	8.99	13.45	7
–10.2	4.97	8.7	6.8	9.14	4.36
–12.7	3.12	4.5	4.9	5.07	2.37
–15.2	2.29	2.3	3.2	2.53	0.94
–17.8	1.36	1.6	2.0	1.17	0.43
–20.3	1.14	1.2	1.2	0.82	0.32
–22.9	0.95	0.95	0.87	0.61	
–25.4	0.82	0.78	0.71	0.47	
–27.9	0.71	0.65	0.59	0.37	
–30.5	0.62	0.56	0.5	0.31	
–33.0	0.54	0.48	0.43	0.27	
–35.6	0.48	0.44	0.37	0.23	
–38.1	0.42	0.38	0.33	0.22	
–40.6	0.37	0.35	0.29	0.2	
–43.2	0.33	0.32	0.26	0.18	
–45.7	0.29	0.29	0.24		
–48.3	0.27	0.27	0.22		
–50.8	0.24	0.25	0.2		
–53.3	0.21	0.23	0.18		
–55.9	0.18	0.21	0.17		
–58.4		0.2	0.16		
–61.0			0.15		

TABLE 2 (Continued)
Irradiance Readings in μW/cm² for a Wall-Mounted UVGI Fixture Equipped with 8.5 W (Nominal Lamp Output) Longline Lamp (Dumyahn and First, in press)

from a wall-mounted fixture containing one tubular lamp rated at 36 W input. It provides data suitable for computer programming to calculate the microbe-killing effect of the fixture in room settings when combined with vertical room ventilation patterns derived from measurement.

DESIGNING UPPER-ROOM ULTRAVIOLET GERMICIDAL IRRADIATION INSTALLATIONS

It is understood that germicidal effectiveness is influenced by room geometry, UV fixture location and power, number of fixtures, and air mixing between the irradiated zones in the upper room and the sources of infectious bacteria that originate in the lower, nonirradiated areas. Inasmuch as these factors are infinitely variable, it is customary to simplify the application process by installing 30 W of UV lamp input power for each 200 ft² (19 m²) of floor area. A typical application might be to install one 30 W wall unit 7 ft (2.1 m) above the floor in the center of one wall of a 14 ft × 14 ft (4.2 m × 4.2 m) room. Rooms of different size, shape, and ceiling height would require different treatment. Another installation guideline that has been proposed is based on a minimum germicidal dose per pass through the irradiated zone of 50 μW·s/cm² (Boehme 1998). Although this dose level is easily achievable and is a more relevant design value in terms of quantitative energy transfer to airborne microbes, it cannot be applied until detailed room air circulation patterns are known and plots of the emission fields of the selected UVGI fixtures have been carefully overlaid on the floor plan. Additionally, one must decide whether to design the installation on the basis of the output UV power of new lamps, old lamps, or something in between. The last is likely to be a good choice. A number of different installations are shown for illustration. All dimensions and wattage figures shown are approximate.

Case 1, Figure 5: A Medical Examination Room and Office

This shows a small rectangular room 14 ft × 10 ft (4.2 m × 3.1 m), 140 ft^2 (13 m^2), with a 9 ft (2.7 m) ceiling. A single, high wall-mounted ultraviolet germicidal fixture centered on the shorter wall can serve this room, directing its output along the longer axis of the space, a favorable geometry. Using the guideline of 30 W of lamp input power per 200 ft^2 (18.6 m^2) of floor area, a 25 W fixture would be appropriate. It should be noted that lamp input can be varied by the manufacturer according to the application and does not include ballast losses. The wall-mounted fixture selected for this application has the following characteristics:

- One 24 in. (0.61 m) slimline lamp
- Fixture input: 49 W
- Tube input: 25 W
- UV output: 8.5 W

Collimated beam (louvered) fixtures are strongly recommended for lower (less than 9.5 ft. [2.9 m]) ceiling applications to control the UV beam pattern and avoid excess eye-level exposure. Typically, they utilize 6 in. (0.15 m) long louvers at ¼ in. (0.6 cm) spacing located in front of the lamp and lamp reflector. Starting with a minimum ceiling height of 8 ft (2.4 m) and the fixture bottom mounted 7 ft (2.1 m) above the floor, the beam sight line extends approximately 24 ft (7.3 m) from the fixture before reaching eye level. This minimum height dimension should be carefully observed, although a small space with short sight lines could be an exception. As the ceiling height increases, fixture mounting height can be increased half the distance of the ceiling height increase, e.g., a 9 ft (2.8 m) ceiling height would permit a 7.5 ft (2.3 m) fixture mounting height. Note in Figure 5 that there is a key-operated switch to control power to the fixture. UV fixtures normally operate continuously, but they must be switched off whenever personnel are present in the upper part of the room (painting, relamping fixtures, cleaning, etc.) or servicing the fixture.

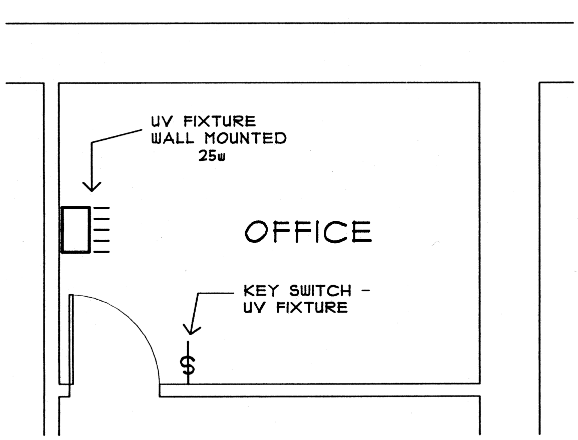

Figure 5 *Case 1: A medical examination room and office.*

Case 2, Figure 6: A Homeless Shelter Dining Hall

Figure 6 shows a large, irregularly shaped dining hall measuring 66 ft × 32 ft (20 m × 9.8 m), 1900ft^2 (180 m^2), with 10 ft (3.1 m) ceiling height. Pendant UVGI fixtures with compact lamps can be utilized effectively to provide well-distributed coverage for this large space. Each fixture contains four 9 W compact lamps. Using the guideline of 30 W/200 ft^2, ten compact pendant fixtures were selected for this application with the following characteristics:

- 40 compact lamps
- Fixture input: 10 × 48 W = 480 W
- Lamp input: 40 × 9 W = 360 W
- Fixture output: 40 × 2.5 W = 100 W

By alternating the fixture suspending stem length of adjacent pendants by 0.5 ft (0.15 m), a thicker band of UV irradi-

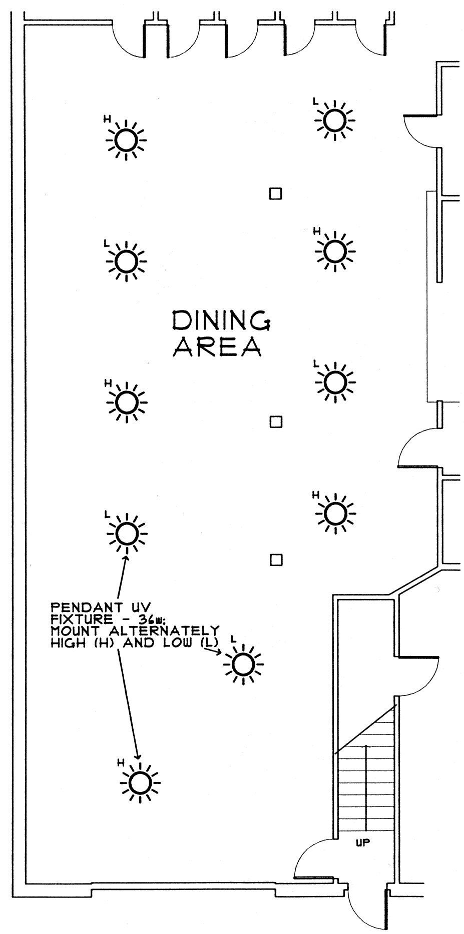

Figure 6 *Case 2: A homeless shelter dining hall.*

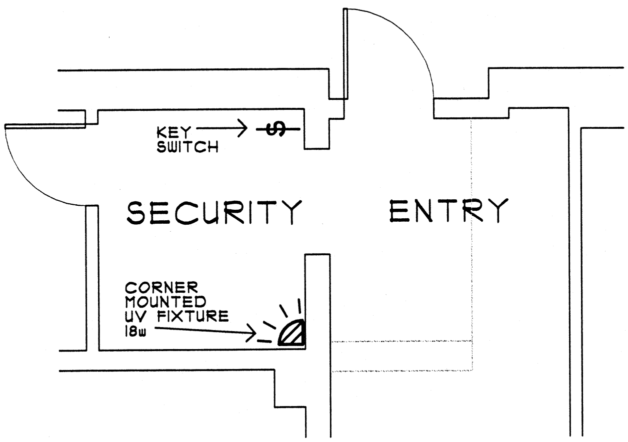

Figure 7 Case 3: A small security station.

ation can be achieved while still maintaining a floor clearance of over 8 ft (2.5 m).

Case 3, Figure 7: A Small Security Station

Figure 7 shows a small room measuring 7 ft × 8 ft (2.1 m × 2.4 m), 56 ft^2, with a ceiling height slightly below 8 ft (2.4 m). Although somewhat below the recommended height, the short sight lines involved make it possible to install a corner-mounted fixture 7 ft (2.1 m) above the floor. The selected corner-mounted fixture has the following characteristics:

- Two compact lamps
- Fixture input: 24 W
- Lamp input: 18 W
- Fixture UV output: 5 W

Case 4, Figure 8: A Drop-In Center Lavatory

Figure 8 shows a toilet room measuring 7 ft × 10 ft (2.1 m × 3.1 m), 70 ft^2, with a 7.5 ft (2.3 m) ceiling. Due to the low ceiling, a UV fan-cabinet unit was selected instead of wall units. The only available installation space was in a corner behind a door. The unit was sited to direct airflow as indicated. The fan-cabinet unit has the following characteristics:

- Listed airflow rate: 325 ft^3/min (11.5 m^3/min)
- Four slimline lamps
- Fixture input: 300 W (including fan motor)
- Lamp input: 120 W
- Lamp output: 45 W

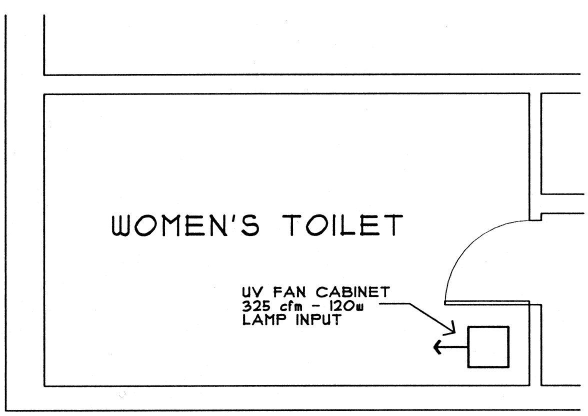

Figure 8 Case 4: A drop-in lavatory.

This unit will provide the equivalent of 15 air turnovers per hour of treated recirculated air in addition to the room mechanical ventilation. The flexibility in locating fan-cabinets units is an advantage, but ensuring good room-air mixing is critical and difficult. The use of UVGI in enclosed air-moving devices poses no danger of exposing people to eye irritation or materials and plants to deterioration. Air is disinfected internally as it is recycled through a compartment of intensive UV irradiation. However, air disinfection rates equivalent to 20 air changes per hour (ACH) are difficult to achieve because of the high flow rates required and the potential for excessive noise and drafts. As indicated by this case, enclosed UV is recommended as a compromise solution for rooms with ceilings too low for upper-room UVGI fixtures. Some fan-cabinet units combine UV with high-efficiency air (HEPA) filtration, but there is no sound reason for using redundant protections, and the filter adds resistance to the fan, increasing noise and energy costs.

Case 5, Figure 9: An Open Stairwell

Figure 9 shows a stair landing with a 12.7 ft (3.9 m) ceiling. A pendant UVGI fixture with compact lamps is used to provide air disinfection. However, care must be taken to avoid line-of-sight UV eye exposure. People descending the stairs from the floor above will, at some point, be looking directly

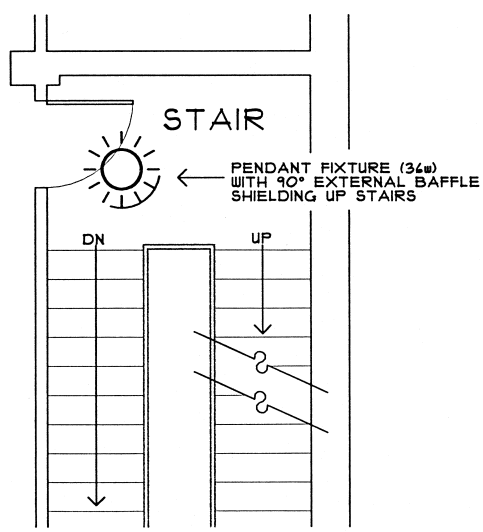

Figure 9 Case 5: An open stairwell.

into the fixture, possibly at relatively close range, although presumably for only a very brief period. To prevent overexposure to the eyes of someone lingering on the stairs, the fixture is provided with a baffle to shield the upstairs sight line. The compact pendant fixture has the following characteristics:

- Four compact lamps
- Fixture input: 48 W
- Lamp input: 36 W
- Lamp output: 10 W

Although a UV level of 0.2 μW/cm² is considered safe for daily exposures for workers, it assumes looking uninterruptedly at the source for the entire period. It is possible to design for somewhat higher UV levels when exposure time is limited to shorter intervals. However, caution should be exercised because space utilization changes made at a later date may negate calculations based on short occupancy periods and put occupants at risk. On the other hand, no one looks steadily at a UV source for eight hours a day, and the recommended standard may contain an excessive safety factor.

Case 6, Figure 10: Corridors and Hallways

Figure 10 shows 365 ft² (34 m²) of corridors requiring UV coverage where ceiling heights vary from a little over 8 ft (2.5 m) to 9.75 ft (3 m). For corridors with low ceilings, wall-mounted fixtures are less obtrusive than hanging pendant fixtures. Although it is necessary to distribute the UV energy up and down the hall, one must be mindful of the long sight lines that complicate provisions for eye shielding. The use of four 18 W hall sconces is a good solution for this application. Each utilizes two 9 W compact UV lamps. The louvers cover a 180° arc, and the fixture is essentially one-half of a compact pendant fixture. Although more fixtures are needed than would be needed if higher-powered fixtures were used, the UV intensity at eye level is better controlled considering the long sight lines. Ceiling heights as low as 8 ft (2.5 m) can generally accommodate sconces at a height slightly over 7 ft (2.2 m), permitting adequate service access. Increasing hall sconce fixture mounting height is desirable as it reduces eye-level UV exposure. The hall sconce fixture has the following characteristics:

- Two compact lamps
- Fixture input: 24 W
- Lamp input: 18 W
- Lamp output: 5 W

Corridors, staircases, and elevator shafts are important pathways for people and permit air exchange between rooms and floors. Therefore, they are pathways for the easy spread of airborne contagion. Careful placement of UVGI fixtures to provide good coverage and adequate levels of irradiance is recommended for all such areas.

Case 7, Figure 11: A Hospital Isolation Room

Figure 11 is a plan view of a hospital isolation room with an attached anteroom. Room area is 190 ft^2 (17.7 m^2) with an 8 ft (2.5 m) ceiling. The preferred location for one 36 W fixture would be over the head of the bed. If this space is obstructed, two 18 W fixtures should be mounted on either side of the head of the bed. Either arrangement provides high levels of UV directly above the patient while reducing eye exposure for 24-hour occupancy. The visible purple light emitted by the UV

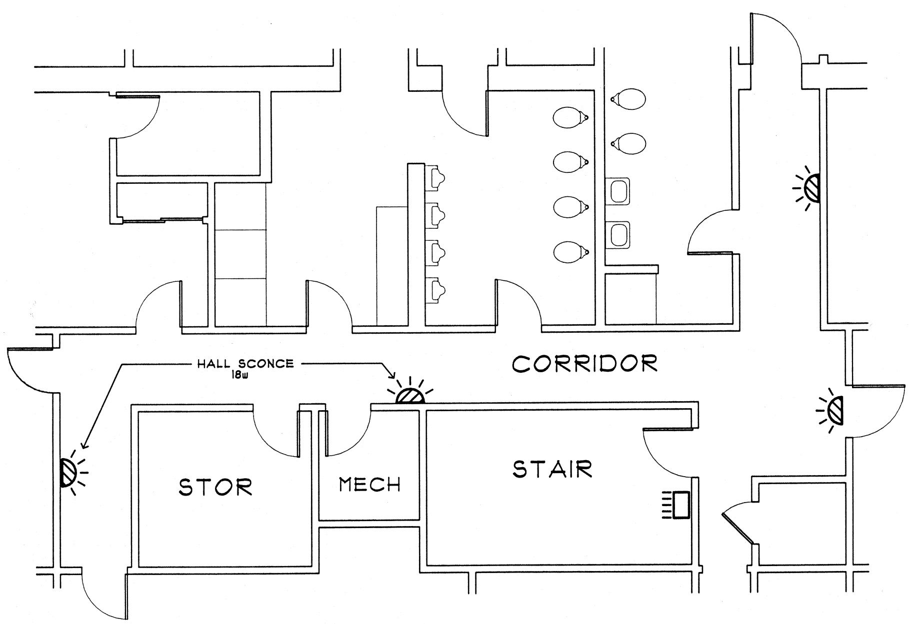

Figure 10 *Case 6: Corridors and hallways.*

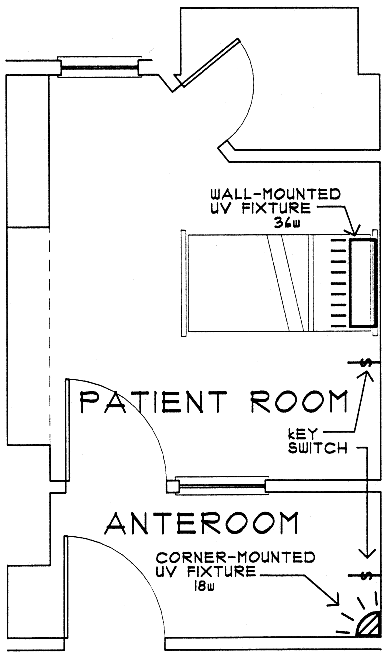

Figure 11 *Case 7: A hospital isolation room.*

lamps is less noticeable in a darkened room when the fixtures are located above and behind. The anteroom is 65 ft^2 (6 m^2) with an 8 ft (2.5 m) ceiling. It can be covered by a single 18 W wall- or corner-mounted fixture. It is recommended that the fixtures be placed so as to avoid a sight line to the adjacent corridor because long sight lines may result in excessive UV irradiance at eye level. The single wall-mounted fixture for the isolation room has the following characteristics:

- Four compact lamps
- Fixture input: 48 W
- Lamp input: 36 W
- Lamp output: 10 W

The corner-mounted fixture for the anteroom has the following characteristics:

- Two compact lamps
- Fixture input: 24 W
- Lamp input: 18 W
- Lamp output: 5 W

These few cases will serve to suggest the range of applications where upper-room UVGI can be applied, as well as illustrate the nature of unfavorable situations.

INSTALLATION, OPERATION, AND MAINTENANCE

UV installations must be designed to provide an adequate irradiance across the entire upper part of the room to effect high levels of microorganism destruction without exposing occupants to danger of transitory eye irritation or skin reddening. Overexposure to UV also produces fading of colors in many paints and fabrics, accelerated deterioration of plastics, and wilting of some plants. Therefore, newly installed systems should not be put into service until an acceptance survey has been performed with a sensitive UV meter containing a detector targeted at the 254 nm wavelength. Lower room UV irradiance should be measured at standing and sitting eye level at representative locations throughout the occupied space. Whenever readings exceed 0.2 $\mu W/cm^2$, the fixtures should be modified to bring irradiance below this level in all areas where people will be stationed for eight hours per day. Sometimes, high readings occur because of reflections from shiny and polished surfaces. White plaster reflects 40% to 60% of 254 nm UV, whereas oil paints reflect only 3% to 10% and water-based paint 10% to 35%. However, UV reflections at a shallow angle may not be predictable. The use of fixtures that are mounted so the aperture is 7 ft or more above the floor and equipped with tightly spaced louvers extending 6 in. (0.15 m) from the UV lamp and tilted slightly upward precludes almost all direct eye contact with a bare lamp. Such fixtures are recommended for most applications.

For UV exposures certain to be less than a full day, intensities higher than 0.2 $\mu W/cm^2$ may be acceptable. The rule is that the absorbed dose ($\mu W{\cdot}s/cm^2$) should not exceed the absorbed dose limit defined by 0.2 $\mu W/cm^2$ for eight hours, equal to 6,000 $\mu J/cm^2$. The relationship may not hold for very high irradiance values, and a large warning label against direct eye exposure should be affixed to a prominent place near or on the exterior of each fixture. Some fixture manufacturers can equip their units with a safety key lock or automatic disconnect when the lamp-access panel is displaced. Another label should show the date on which the lamp was put in operation so it can be replaced at the end of the rated life, stated by the manufacturer. When dirty, tubes should be turned off and cleaned with a cloth dampened with alcohol. Reflectors should be cleaned simultaneously by the same method. In relatively dust-free areas, such as most health care facilities, frequent cleaning may not be needed.

UVGI fixtures should be on separate circuits from lighting fixtures, and the switches should be key operated to prevent unauthorized use. Upper-room germicidal systems should be left on continuously, day and night, as frequent switching, especially with operating intervals of three hours or less, materially reduces lamp life. However, lamps should always be turned off when workers are in the upper part of the room for painting or maintenance work and when lamps are inspected or changed. Usually, lamps are discarded when they decline 30% from their 100-hour rating. Many users choose to install new lamps annually as the decline occurs around that interval.

Low-pressure mercury lamps are characterized by a relatively low power load and a consequently low glass wall temperature. It is important to keep the lamp within close temperature limits because the pressure of the mercury vapor governs the UV power output. For example, the output at 32°F is 25% lower than at 68°F when the lamp is in a still air loca-

BACK TO PAGE ONE

tion but can decline still further when there is enough airflow past the lamp to cause more rapid heat loss. This is seldom a problem in indoor spaces except for facilities such as ice skating rinks or refrigerated spaces. High temperature will reduce output and can be a hazard if it leads to overheating of the ballast.

When UV-sensitive plants, plastics, and colored fabrics cannot be removed from irradiated areas, they can be covered or shaded with ordinary glass as it is opaque to UV radiation and provides protection.

Sometimes, UV fixtures that are installed to "disinfect" unoccupied rooms are sold with bare lamps. This is potentially dangerous due to the chance of direct, intense UV eye exposure. This use of germicidal UV irradiation is both unnecessary and ineffective because of the poor penetrating power of 254 nm UV and because the risk of TB and many other airborne infections exists only in the airborne state. On surfaces, deposited mycobacteria and most other human pathogens have a half-life of no more than six hours under ideal conditions and are unlikely to be re-aerolized.

COST COMPARISONS

The cost comparison figures given here are meant to be indicative of the relative scale of purchase, installation, and operating costs for hospital-grade HVAC equipment and UVGI equipment to provide an increment of 6 ACH, or the equivalent germicidal effect, in treated spaces. The comparison lacks some coherence because the HVAC costs relate to Boston, whereas the UVGI costs relate to New York City and Birmingham, Alabama. Nevertheless, it is expected that the cost information will at least indicate the scale of the absolute and relative costs and fill an information gap that has long awaited some reasonable attention.

The basic data came from three sources, all recent.

1. Hospital grade HVAC units average \$30 - \$35/ft^2 and \$1.50 - \$1.75/cfm of capacity (Srisisikul 1998). We will use the lower figures.
2. Recent UVGI equipment purchase and installation costs for New York City were \$277,000 for 185 units with a total energy input of 7,376 W. This installation serves a floor area of 36,000 ft^2, or \$7.60/ft^2 (Vincent 1997). These values work out to 41 W per 200 ft^2 of floor area and 20 W per 1,000 ft^3 of enclosed volume. In Birmingham, the UVGI equipment purchase and installation costs were \$147,000 (two-thirds installation, one-third equipment) for 139 fixtures serving a floor area of 13,000 ft^2, or \$11.30/ft^2 (Vincent 1997). These values work out to 67 W per 200 ft^2 of floor area and 38 W per 1,000 ft^3 of enclosed volume. We will use the higher Birmingham costs in our comparison.
3. Annual operating costs saved for a 6 ACH reduction for a 9,000 ft^3 space in Boston are estimated to be \$4,500, or \$5/cfm (Beaudoin 1998). Using the above figures plus an electricity cost of \$0.1 kWh, it is possible to compare purchase and operating costs for a 6 ACH unit on the basis of floor area—first, equipment and installation costs and then, annual operating costs. The comparison will be made on the basis of 6 ACH per 1,000 ft^3 of space provided with HVAC or avoided by the alternative cost of UVGI. The air exchange rate would be 6,000 ft^3/h or 100 cfm. The HVAC equipment cost would be \$30/ft^2, whereas the Birmingham UVGI installation cost was \$11.30/ft^2.

For operating costs, the annual HVAC Boston estimate is \$1.50/cfm of capacity. To serve 1,000 ft^3 of enclosed space for 6 ACH, the requirement would be 100 cfm @ \$1.50/cfm or \$150/year. For Birmingham, the electrical cost for 1,000 ft^3 of enclosed space is 38 W per 1,000 ft^3 multiplied by 8,760 hours per year and \$0.1/kWh to give \$33.

It is understood that both systems require maintenance, but these costs were not estimated. It is also understood that for some applications a fraction of conditioned air can be recirculated, thereby lowering HVAC operating costs. The UVGI installation costs for Birmingham were unusually high because the building contained a large number of small cubicles that resulted in almost double the recommended UV capacity (i.e., 67 W per 200 ft^2 instead of 30 W per 200 ft^2). Nevertheless, these crude estimates of purchase, installation, and operating costs show that UVGI is a less expensive option for equivalent air sanitation effectiveness.

DISCUSSION

Guidelines for the design and installation of upper-room UVGI systems have been published from time to time by a number of lamp and fixture manufacturers over the past half century of their use, but basic engineering studies and technical publications devoted to the technology are scanty and not susceptible to broad generalization. This is in contrast to the large body of literature pertaining to laboratory studies of the response of a long list of microorganisms to graduated doses of UV germicidal irradiation under a wide range of temperature and humidity conditions. Fortunately, the situation is beginning to change for the better with the development of improved methods for evaluating the distribution of energy from modern lamps and fixtures and the introduction of computational fluid dynamics (CFD) studies. These studies are intended to define the microstructure of room air movements and integrate this information with the distribution of the UV irradiance field to measure the effective UV dose to airborne microorganisms and, ultimately, to evaluate effectiveness quantitatively. Until research results are published that make CFD analytical methods readily available to engineers for designing optimum-efficiency UVGI installations, reliance must be placed on experience and the application of empirical methods derived from it. Through case studies similar to those presented here, which seek to explain the rationale for equipment selection and location in spaces of different geometry and function, the knowledge needed to employ this technology currently can be shared.

Confirmation of the effectiveness of upper-room UVGI must be sought through epidemiologic studies. In this area,

BACK TO PAGE ONE

also, published results are scanty, but concern over the recent resurgence of tuberculosis has stimulated interest, and definitive studies are underway to examine the effectiveness of upper-room UVGI in preventing tuberculosis transmission in situations where close contact with infected individuals occurs frequently. In the meantime, extrapolating from convincing laboratory data on germicidal effectiveness, plus the lessons learned from the successful transmission studies reported in the literature, give firm support to the empirical engineering design methodology currently in use.

CONCLUSIONS

Upper-room ultraviolet germicidal irradiation technology is an economical substitute for increased mechanical air exchange rates as an effective means of improving air hygiene and reducing communicable airborne disease transmission. Modern equipment that takes into consideration the general lowering of ceiling heights and concerns for eye protection are available from a number of commercial sources, and there is an adequate body of engineering experience to guide design and installation.

REFERENCES

Beaudoin, D. 1998. Personal communication, March 3. Operations Office, Harvard School of Public Health, Boston, Mass.

Boehme, H. 1998. Personal communication, June 5. Atlantic Ultraviolet Corp., Hauppauge, N.Y.

Dumyahn T., and M. First. Characterization of ultraviolet upper-room air disinfection devices. *Am. Ind. Hyg. Assoc. J.*, in press.

First, M.W., E.A. Nardell, W. Chaisson, and R. Riley. 1999. Guidelines for the application of upper-room ultraviolet germicidal irradiation for preventing transmission of airborne contagion—Part I: Basic principles. *ASHRAE Transactions* 105(1).

Srisisikul, T. 1998. Personal communication, April, 16. Massachusetts General Hosp., Boston.

Vincent, R.L. 1997. Personal communication, December 5. TB/UV Shelter Study Program, New York, N.Y.