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High-output UVC emitter.

Using UVC Technology To Enhance IAQ

A new UVC technology overcomes previous limitations to enhance IAQ control, effectively and efficiently killing microorganisms that grow, disseminate, and circulate in air handling systems

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In the popular movie *Outbreak*, there is a pivotal scene in which the camera zooms through the air conditioning ductwork of a hospital, revealing the terrible discovery that a deadly virus previously thought to be transmitted only through direct contact is, in fact, airborne and being delivered room to room. The scene graphically drives home the point that infectious diseases can be and often are, transmitted through the air and further, that the air handling systems in today's buildings provide efficient conduits for the spread of such diseases. And in the TV movie *Virus*, the Max 4 lab containing the deadly Ebola virus shows the familiar blue hue of ultraviolet light fixtures bathing the entire area with UVC to provide sterility in the event of an accident.

Drug-resistant bacteria and new viruses are triggering an alarming increase in infectious diseases worldwide.[1] Although the AIDS virus is the best publicized example, it is estimated that the major airborne-transmitted infectious diseases (acute respiratory infections, tuberculosis, measles, and pertussis) account for some 8.5 million deaths per year around the world.

Air handling systems are not only potential conduits for the spread of disease, they are sometimes the cause of the problem. Legionella microorganisms, which enter and grow in HVAC systems, are the most notorious example. Less dangerous but far more typical is the growth of mold, the most common form of allergen. In the dark, moist environment of an HVAC system, mold spores can proliferate year-round. With allergic individuals, these spores initiate a chain of reactions starting with the release of histamines and inflammation of mucus membranes. These symptoms may lead to congestion, breathing difficulties, or even asthma and other complications.

There are several categories of organisms that can grow and/or spread in modern air handling systems:

▼ **PATHOGENS**—viruses, bacteria, and fungi that cause a range of infectious diseases.

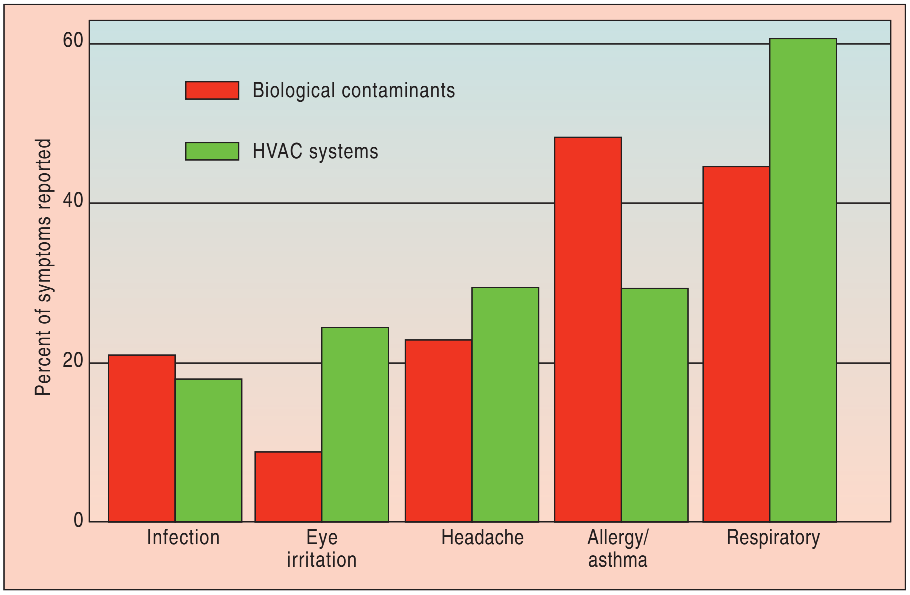
▼ **ALLERGENS**—bacteria and mold that cause allergic rhinitis, asthma, humidifier fever, and hypersensitivity pneumonitis.

▼ **TOXINS**—endotoxins and mycotoxins that cause a variety of toxic effects, irritation, and odors.

As HVAC systems move large amounts of outdoor and recirculated air through occupied buildings, they become the conduits by which these unhealthful organisms are spread throughout the spaces they serve.

In the ongoing quest for better indoor air quality (IAQ), experts have come to recognize that these biological contaminants in indoor air are major contributors to sick building syndrome and building-related illness (Fig. 1). In fact, according to the World Health Organization, biological contaminants in buildings are believed to account for a substantial portion of absences from work and school as well as days where activity is impaired or restricted. As a comparative, in most cases, the cost of

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



1 IAQ-related symptoms. **(Source: Air Resources Board, California EPA)**

losses in productivity far exceeds the cost of operating and maintaining the HVAC system.[2]

Common control strategies

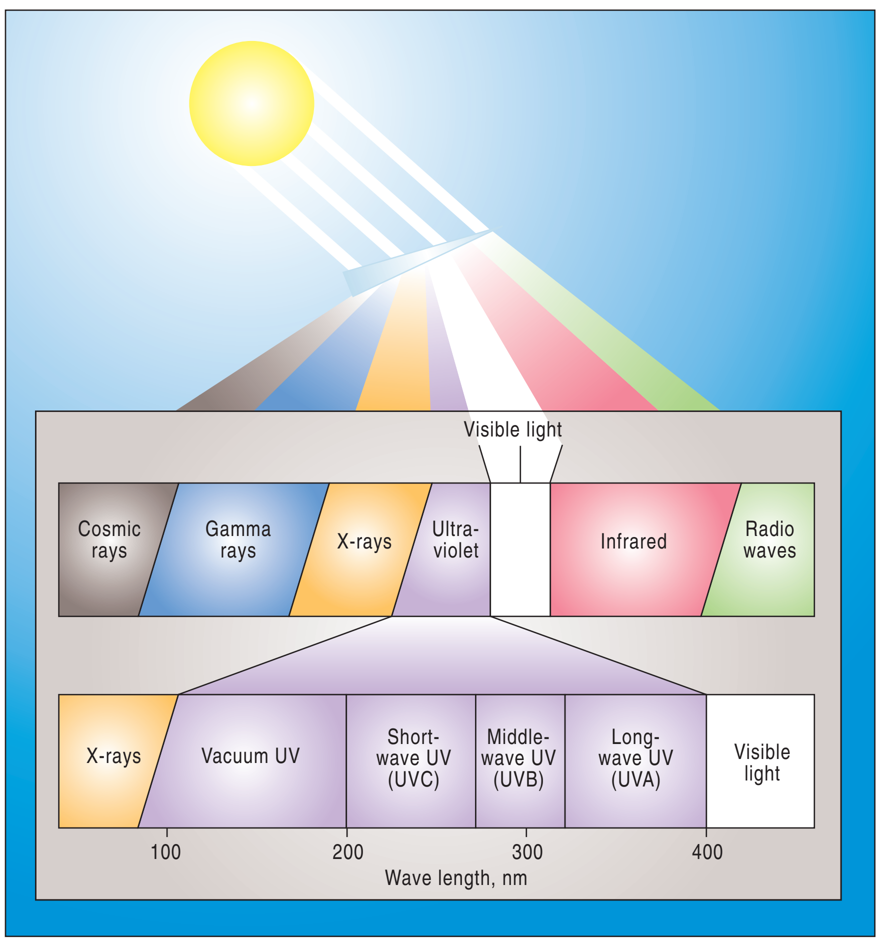
Biological contaminants are also among the most difficult to control. Though high-efficiency ASHRAE-grade or HEPA filters are helpful, many systems do not lend themselves to filter upgrades without major changes. And since many microorganisms are typically less than 1 micron in size (with some viruses as small as 0.003 to 0.004 micron), even high-efficiency filtration may be inadequate.

Another very important but overlooked issue is a condition that may occur when time-clock systems are turned off. Natural temperature differentials between the system and the space create a convection flow or "backdraft" effect that returns space contaminants back through the ductwork to the downstream side of the filters. When combined with system leaks, these conditions often compromise the filters' role.

Where biological contamination is known to exist, a common control strategy is duct cleaning, sometimes followed by a biocidal treatment. In subsequent swab sample testing, however, biological activity of concern has often been demonstrated to return in as little as three months after cleaning and treatment. In cases where *legionella* microorganisms are present or suspected, acid washing (or other treatment) of fan-coils, drain pans, cooling towers, etc., is required—an expensive and often destructive procedure that shortens equipment life. Other methods for microorganism control tend to be impractical, potentially toxic, detrimental to equipment operation and efficiency, or simply too costly.

Enter ultraviolet (UV) technology into the equation. UV light (Fig. 2) in the form of germicidal lamps has been used since the late 1800s to kill the same types of microorganisms that typically cause IAQ problems. Niels Ryberg Finsen (1860 to 1904), a Danish physician, was the first to employ UV rays in treating disease and ultimately invented the Finsen curative lamp, which was used successfully into the 20th century.[3]

Since then, UV radiation in the short wave or C band range (200 to 280 nanometers) has been used in



2 Radiant energy.

a wide range of germicidal applications to destroy bacteria, mold, yeast, and viruses. After World War II, the use of UVC increased rapidly for upper air (where UV was directed as a beam across the ceiling of a room) and other applications. Typical examples included hospitals, beverage production, meat storage and processing plants, bakeries, breweries, dairies, kitchens, pharmaceutical production, and animal labs—virtually anywhere that microbiological contamination was of concern.

As mechanical ventilation of these spaces became popular, however, it was found to have an adverse effect on UVC performance. The introduction of moving air over the tubes, especially below 77 F, decreased the output and service life of conventional UVC products and thus their ability to destroy viable organisms. Additional lamps were installed and changeout cycles accelerated to compensate for these problems.

During the 1950s when tuberculosis (TB) infections were on the rise, the use of UVC broadened further in scope. In addition to upper air applications, it found its way into air handling equipment and became a major component in the control and eradication of TB.

Over the next decade, with the availability of new drugs, sterilizing cleaners, and control procedures (gowning, etc.), concern over microbiological problems began to wane. This trend, coupled with the performance problems of UVC lamps in air handling systems (impaired output, short tube life, and high maintenance), caused the use of UVC in HVAC equipment almost to disappear. Despite this fact, ASHRAE has acknowledged the effectiveness of UVC, stating that "Sterilizing lamp installations in duct systems have been reported to be highly efficient."[4]

High-output emitters

Recently, there have been significant strides in the development of UVC light production sources. A patented UVC emitter seems to defy the accepted operating principles of germicidal lamps manufactured over the last 50 to 70 years in that its output actually *increases* in the "hostile" operating environments of cold and/or moving air. In development for 16 years, this new technology combines unusual voltages, excitation wave forms, discharge ignition, and a unique blend of gases and vapors to produce a high output and very stable broad-band ultraviolet energy. Although germicidal effectiveness is believed to be greatest at 265 nm (Table 1), the spectral overlap of newer devices at other UVC wave lengths causes these broad-band emitters to be more efficient.

TABLE 1 – Germicidal effectiveness.

Wave length, nm	Relative germicidal effectiveness
240	0.62
245	0.76
250	0.90
255	1.03
260	1.12
265	1.15
270	1.08
275	0.98
280	0.87
285	0.73
290	0.60

Germicidal UVC energy penetrates the outer structure of the cell and alters the DNA molecule. This prevents replication, causing cell death. Germicidal effectiveness of UVC is directly related to the dose applied, and the dosage is the integral product of *time and intensity*. A high intensity for a short period of time and low intensity for a long period of time are nearly reciprocal and are equal in killing power; therefore, the energy required to destroy microorganisms is given as microwatt-seconds (or microjoules) per square centimeter.

Independent testing performed by Rapid Precision Testing Laboratories, Cordova, Tenn. (Table 2 and Fig. 3), has shown that when compared to the older generation of UVC lamps, high-output UVC emitters specifically designed for HVAC use:

▼ Consume only 1.75 times the electrical power yet produce 2.5 to 6 times the output at temperatures ranging from 32 to 90 F.

▼ Produce over five times the output at conditions most often found in HVAC systems.

▼ Produce a wider band width for more killing power at a broader spectrum.

▼ Provide a significant increase in output per inch (arc length) of tube (footprint) as well as an increase in tube life, meaning that fewer tubes can be used for a longer period of time. Significant life-cycle cost reductions over conventional designs are the end result.

As noted in Table 1, scientific research has concluded that maximum germicidal effectiveness occurs at about 265 nm. There are no low-pressure, mercury vapor UVC devices currently available that produce this optimum spectral line. However, as demonstrated in Fig. 3, some high-output emitters can deliver a broader band of total output (250 to 260 nm), so in addition to the benefit of increased output, they are closer to the optimum wave length, thus further enhancing available effectiveness.

Field experience to date with high-output emitters has been uniformly positive. For example, a southern California hospital, which is taking a highly proactive approach to IAQ control, recently brought in expert diagnosticians to measure microbial activity. Their analysis uncovered the presence of various types of mold spores in one of the air handling systems despite the use of 95-percent ASHRAE efficiency filters in a tightly sealed housing. It is important to recognize that high-efficiency ASHRAE filters do not remove all microorganisms and that mold may still develop when organism-laden air is permitted to enter the air handling system—*e.g.*, during time-clock operated shutdown (backdraft), when access doors are opened for filter changes, etc.

Though the initial mold count (taken during winter months) was low, the hospital wanted to guard against the typical summer mold proliferation and installed three high-output UVC emitters downstream of the filters—enough irradiance to provide effective kill of surface organisms within the 8000 cfm system. Subsequent surface testing of the area showed that the UVC lamps yielded a tenfold reduction in mold count. By doubling the number of lamps to six, the hospital expects to achieve a hundred-fold reduction in both surface and potentially airborne microorganisms.

A number of high-output UVC systems were also installed in the residences of individuals suffering from hypersensitivity pneumonitis. In these applications, the UVC emitters proved to eradicate mold and other organisms within a very short period of time, effectively relieving allergy symptoms. In cases where 25 percent of the light sources were permitted to burn out, individuals in the test homes noticed an immediate return of symptoms, demonstrating the importance of maintaining a prescribed amount of irradiance to sustain kill rates.

Properly sized, installed, and maintained, a high-output UVC light system can be a significant control strategy to help reduce or eliminate discomfort or incapacitation caused by microbiological reactions, *legionella* microorganism growth and airborne dissemination, circulation of tuberculosis in air handling systems, and spread of cold and flu viruses. Equally important, the high-output emitters operate without producing ozone or outgassing fumes or generating secondary contaminants. They kill harmful microorganisms without posing a risk to building occupants, maintenance personnel, mechanical equipment, and interior furnishings.

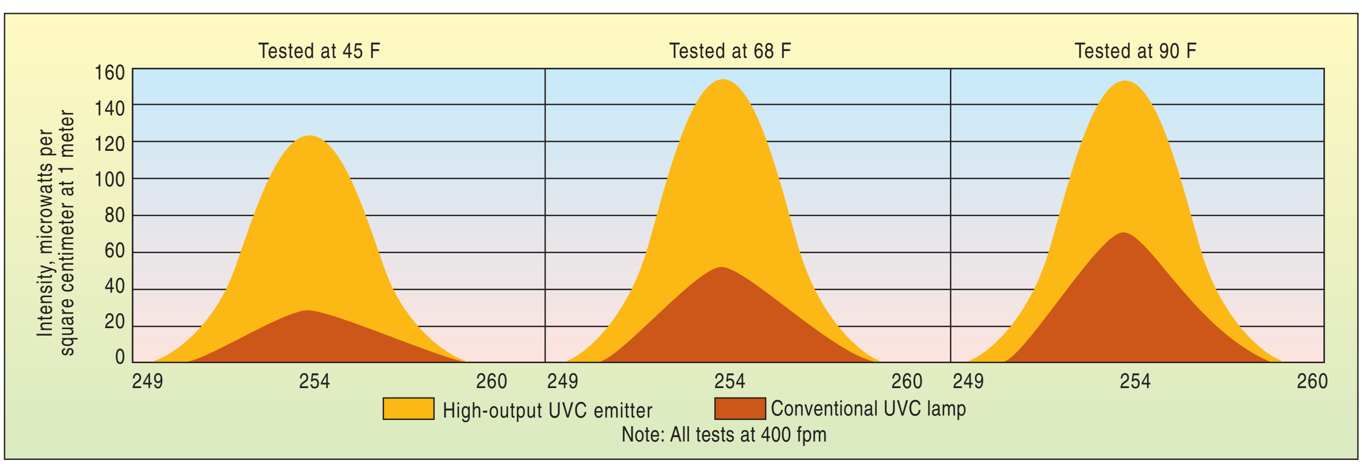
Key considerations

When setting up a high-output UVC sterilization system in air handling equipment, one can apply a simplified formula for roughing in the approximate number of emitters needed in ducts or plenums. The following formula is based on providing a 90 percent deactivation of the standard test microorganism *Escherichia coli* (*E. coli*) in air temperatures from 45 to 90 F and up to 60 percent relative humidity, with air velocities of 200 to 800 fpm and zero duct reflectance: N = cfm/30d, where N is the approximate number of lamps required and d is the smallest cross-sectional dimension of duct in inches. For example, to calculate the number of high-output emitters required for 11,000 cfm of air

TABLE 2 – Physical output characteristics of high-output UVC tubes versus standard UV tubes.

	High-output UVC emitter	Typical G 25 T8	Typical G 36 T6
Nominal length	16 in.	18 in.	36 in.
Arc length	11 in.	14 in.	29¼ in.
Tube outside diameter	⅝ in.	1 in.	⅝ in.
Wall thickness	Heavy	Thin	Thin
UV output at 1 meter:			
68 F at 400 fpm	158 μW/cm^2	50 μW/cm^2	80 μW/cm^2
45 F at 400 fpm	122 μW/cm^2	23 μW/cm^2	>38 μW/cm^2
μW/in. arc length, 45 F at 400 fpm	11.1 μW	1.64 μW	1.30 μW
Power supply	Special	Magnetic	Slimline
117Vac power draw at 45 F	72 W	47 W	>100 W
UV increase per inch over baseline of 1.0	1110 percent	164 percent	130 percent
UV band width	Wide	Narrow	Narrow
Ozone output	Nil	Nil	0.03 ppm
Average tube life	9000 hr	5000 hr	7500 hr
Operating conditions	Hostile	Ideal	Ideal
UL certification	U/L 1995	Component level only	Component level only

3 Germicidal output comparison.



carried by a 60 by 66 in. duct: $N = 11{,}000/(30 \times 60) = 6$ UVC emitters (approximately).

To guarantee anticipated results, however, one must use a variety of physical and operating factors to determine the actual number of lamps needed, their placement, and any minor modifications that may be required to existing ductwork or other components. When working with UVC, one should consider the following questions during planning:

▼ *What are the targeted organisms?* If UVC emitters are to be used for general microbial control, *E. coli* (as above) is accepted as the standard. However, if a specific organism is to be targeted, one must determine the right UVC dosage for that organism. Table 3 shows the amount of 253.7 nm energy required, in microwatt-seconds per square centimeter, to destroy 90 percent of various common organisms.

These data come from decades of research work by several parties;[5] however, most of the research performed was done using petri dishes of specific cultures. It is noteworthy to point out that these organisms were struck by UVC photons at a very narrow plane (assumed to be less than 160 deg), and some of the energy may have been attenuated by the agar used. By comparison, aerosolized microorganisms are struck at global angles of 360 deg and actually receive an even greater number of protons through proper placement of lamps and reflectance. Thus, it is believed that airborne microorganisms can actually be destroyed using considerably less UVC energy than is indicated in Table 3. Independent tests are currently under way to measure the efficacy of UVC on airborne microorganisms. When available, results will prove to be invaluable in the design of UVC systems for HVAC applications.

▼ *What is the desired deactivation or "kill" rate?* A kill rate of 90 percent (based on single-pass testing with conventional measurements) is accepted as the standard for general microbial control in IAQ situations. This rate will deliver nearly a log reduction in microbial contamination, achieving indoor air quality that is roughly equivalent to that of outdoor air. In highly sensitive applications, however, or in areas where harmful microorganisms are being targeted, a higher deactivation rate may be desired. By increasing the number of lamps and/or reflectance, one can achieve deactivation rates of 99.9 percent and higher.

▼ *What is the air velocity within the system?* Velocity, expressed in fpm, is a key factor in determining the time an organism spends within the physical cavity (sometimes referred to as "dwell time") and the amount of heat removed from the UVC lamp, which directly affects its output. Thus, the higher the velocity, the more UVC energy required to achieve desired performance.

▼ *What is the temperature within the system?* Temperature, in conjunction with velocity, determines the absolute heat removal capability of the system and its effect on the UVC device. As previously noted, conventional UVC lamps suffer unacceptable losses in output when exposed to cold and/or moving air. Some high-output devices, by contrast, continue to function efficiently under these conditions. Variations in temperature and velocity, nonetheless, have enough influence on output to require being taken into account.

▼ *What is the relative humidity of the system?* Humidity is an attenuator to UVC energy. The simplified formula above applies to the typical moisture levels found in the recirculated air of HVAC systems. If higher (greater than 60 percent) relative humidity exists, more UVC energy is needed to compensate for the absorption effect.

▼ *How can the physical cavity (the area to be irradiated) be defined?* The simplified formula only considers a single-plane dimension of the space to be treated with UVC radiation. In real applications, however, one must characterize and dimensionalize that space or physical cavity more precisely. Internal mechanical components, for example, not only reduce the total cubic space but also partially obstruct UVC radiation. The physical cavity must therefore by "mapped" as accurately as possible to ensure proper design and placement of UVC light sources.

▼ *Where are the light sources to be located?* High-output emitters may be installed in a variety of locations to maximize kill percentages: anywhere in the supply side of the system, before and/or after the evaporator coil, and within the mixed air plenum or return duct. With their increased output and smaller footprint, they may even be

TABLE 3 – Germicidal energy required to destroy common microorganisms.

Microorganism	Energy, μW-sec/cm²
Bacteria	
Bacillus anthracis	4,520
Bacillus megaterium	1,300
Bacillus megaterium spores	2,730
Bacillus subtilis	7,100
Bacillus subtilis spores	12,000
Corynebacterium diphtheriae	3,370
Escherichia coli	3,000
Micrococcus lutea	19,700
Micrococcus spheroides	10,000
Neisseria Catarrhalis	4,400
Proteus vulgaris	2,640
Pseudomonas aeruginosa	3,500
Pseudomonas fluorescens	8,000
Salmonella enteritidis	4,000
Salmonella typhimurium	8,000
Serratia marcescens	2,420
Shigells paradysenteriae	1,680
Spirillum rubrum	4,400
Staphylococcus albus	1,840
Staphylococcus aureus	2,600
Streptococcus hemolyticus	2,160
Streptococcus lactis	6,150
Streptococcus viridans	2,000
Yeasts	
Saccharomyces cerevisiae	6,000
Saccharomyces ellipsoides	6,000
Brewer's yeast	3,300
Baker's yeast	3,900
Mold spores	
Aspergillus flavus	60,000
Aspergillus glaucus	44,000
Aspergillus niger	132,000
Mucor racemosus	17,000
Oospora lactis	6,000
Penicillium digitatum	44,000
Penicillium expansum	13,000
Penicillium roqueforti	13,000
Rhizopus nigricans	111,000

used in cavities never considered before, such as heat pumps, packaged equipment, unit ventilators, and fan-coil units. Due to variations in temperature, velocity, and other factors (as above), location has an impact on performance. For example, a UVC sterilization system upstream of the evaporator coil has different energy requirements than one located downstream of the coil.

▼*What is the irradiance value?* The simplified formula assumes that the light irradiance value (flux in microwatts per square centimeter) is at the midpoint of the duct or plenum, or approximately half the distance of the value for *d*. By using the intensity factor chart (Table 4), one can determine the actual irradiance at a specific distance. The irradiance factor or potential dose increases with the number of photons available to strike a target microorganism. The greater the irradiance, the higher the kill rate for that microorganism. For example, ignoring other factors, achieving a 99.99 percent kill versus a 90 percent kill mathematically requires four times the irradiance or number of emitters.

TABLE 5 – Surface reflectance.

Material	Reflectance, percent
Magnesium oxide	75 to 90
Polished aluminum sheet	60 to 90
Aluminum paint	40 to 75
White plaster	40 to 60
Chromium	40
Nickel	40
Stainless steel	25 to 30
White water paint	10 to 35
Typical duct liner	0 to 1

▼*How can surface reflectance be optimized?* Last but not least, surface reflectance is a key factor in the design of an HVAC UVC sterilization system, and it directly relates to the value of total irradiance. Reflectance within the cavity creates a global ricochet effect of generated photons, making a higher number of them available and bouncing them in all directions to penetrate every nook and cranny—in effect, potentially increasing the dosage received by any organism. Thus, irradiance can be greatly enhanced by ample reflectance. In addition, organisms in submicron dust or droplets may be shielded from UVC. Reflectance works literally to "unhide" these organisms for proper destruction. Kill rates are thus further improved.

What's considered a good reflectant for visible light, however, is not always a good reflectant for the invisible light energy of UVC. For example, common glass totally attenuates UVC; therefore, a typical rear-surfaced glass mirror does not reflect UVC at all. Table 5 provides examples of the reflectance of various surfaces to UV light of 254 nanometers. Since a typical duct liner has little or no reflectance, practical solutions include coating surfaces with aluminum paint or lining them with aluminum foil or sheeting.

TABLE 4 – Intensity factor.

Distance from lamp, in.	Intensity factor
2	32.3
3	22.8
4	18.6
6	12.9
8	9.85
10	7.94
12	6.48
14	5.35
18	3.6
24	2.33
36	1.22
39.37 (1 m)	1.00
48	0.681
60	0.452
80	0.256
100	0.169
120	0.115

By evaluating all of these interrelated factors, the HVAC system practitioner can design the best possible high-output UVC system for the job. It is interesting to note that, depending on the operational characteristics of the HVAC equipment, it can take five times or more the number of conventional UVC lamps—and more than three times the power input—to achieve the same results.

Conclusion

Though UVC sterilization has been proven for many decades, the use of high-output UVC designed specifically for HVAC systems is still in its infancy. The technology promises to be of great humanitarian value in a wide range of IAQ applications. Initial uses have consisted chiefly of retrofit installations in buildings and residences where real or perceived air quality problems have been reported; however, UVC can be equally effective as a "value-added" HVAC feature in new construction of schools, hospitals, and other public and commercial buildings. As updated test and field performance data become available, perhaps then and only then will this new generation of UVC emitters achieve its full potential. **HPAC**

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