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Case Study

Evaluating Ultraviolet Germicidal Irradiation

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Ultraviolet germicidal irradiation (UVGI) of air is a proven technique for controlling infectious aerosols.[1] This column summarizes an evaluation of in-duct UVGI proposals for several buildings under the control of one owner and operator with the purpose of reducing COVID-19 transmission. The column also briefly discusses upper-room UVGI.

My company reviewed and evaluated proposals and dose calculations from two qualified vendors and clarified their scope in discussions and emails. Based on our evaluation of sample calculations, the proposals were estimated to provide enough ultraviolet (UV) lamp intensity to achieve 90% kill rate for SARS-CoV-2. We recommended the following if the owner decides to implement in-duct UV:

- The contract should be contingent on review and approval by a qualified third party of preconstruction submissions including detailed UV dose calculations based on air handler geometry, UV lamp location, air velocity and other specific data for each AHU.
- The additional maintenance (lamp replacement, etc.) and energy cost should be accounted for in owner budgeting.

However, our evaluation concluded that UVGI is several times more expensive to install and operate than previously estimated in the *2019 ASHRAE Handbook—HVAC Applications*. Therefore, we recommended that the owner first exhaust more basic options that include filtration, dilution with outside air, verification of airflows and recommissioning. This case study may be useful in guiding others in evaluating other real-world proposals for using UVGI to control infectious disease aerosols.

Price Summary and Comparison

Table 1 summarizes the prices from two vendors. Both vendors relied on suppliers for the UV products and for calculations of the dose and lamp intensity required.

Installation Features

Following are some features provided in either or both of the proposals that are necessary for a complete installation or are enhancements that are worth considering, in addition to price:

- Electric power to lamps;

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- Lamp operation indicator and view window;
- Airflow switches to "prove" airflow prior to energizing lamps;
- Door switches to de-energize lamps and caution signs for personnel safety;
- Run-hour meters to track use and estimate lamp end of life; and
- Lamp encapsulation to protect against breakage and to improve lamp output by insulating them from cool air.

TABLE 1 Price comparison in-duct UVGI.

BUILDING 1 THROUGH 4	QUANTITY OF AHUS	AREA (FT^2)	VENDOR A PRICE ($)	VENDOR B PRICE ($)	LOWER OF A AND B PRICE FOR EACH BUILDING ($)	LOWER COST IN $/$FT^2$
1	1	8,490	8,144	10,260	8,144	0.96
2	10	95,700	154,519	92,357	92,357	0.97
3	16	16,236	73,672	80,580	73,672	4.54
4	15	181,811	214,627	196,008	196,008	1.08
BUILDING NUMBER 1 THROUGH 4 SUBTOTAL	42	302,237	450,962	379,205	370,181	1.22
BUILDING 1 THROUGH 4 PRICE/FT^2	–	–	1.49	1.25	1.22	–
BUILDING NUMBER 5 AND 6	QUANTITY OF AHUS	AREA (FT^2)	VENDOR A PRICE ($)	VENDOR B PRICE ($)	LOWER OF A AND B PRICE FOR EACH BUILDING ($)	LOWER COST IN $/$FT^2$
5	12	165,000	No Bid	174,406	174,406	1.06
6	2	70,652	No Bid	22,148	22,148	0.31
ALL BUILDINGS TOTAL	56	537,889	450,962	575,759	566,736	1.05
BUILDING 1 THROUGH 6 VENDOR PRICE/FT^2	–	–	1.49	1.07	1.05	–

The competitively bid average low price of $1.22/ft² ($13.13/m²) is five to nine times higher than the estimated cost of $0.13/ft² to $0.25/ft² ($1.40/m² to $2.69/m²) in the *ASHRAE Handbook—HVAC Applications*.[1]

Comparison to ASHRAE Standards

ASHRAE Standard 185.2-2020[2] describes a method of test to generate a performance report for a UVC device but does not provide a pass-fail criterion for the device. The test setup includes 10 ft (3048 mm) of duct up and downstream of the device, which is likely to be larger than an actual air handler. Therefore, the test report may be useful for comparing products, but it does not predict performance in a particular field application. Neither vendor provided such test data.

Vendor B said, "while we meet Standard 185, the only lab that was ever certified to test for that (RTI) is closed so no UV companies were ever tested. The design standards for 185.1/185.2 are met." However, as described above, "meets" is not a criterion in Standard 185.2-2020.

Effectiveness and Kill Rate

The approximate lamp intensity included in the proposals from both vendors seems more than enough to achieve a kill rate of 90% or more for SARS-CoV-2, based on a calculation check we performed,* *provided that there is 2 ft (610 mm) in the direction of airflow in the plenum where the UV lamps are located* and the lamp is installed in the middle. The longer the plenum length, the higher the dose and the kill rate. Shorter plenums have a correspondingly shorter residence time and require higher lamp intensity to achieve the same kill rate as a longer plenum.

The formula to calculate survival rate of a microbial population is:

$$S = e^{-kIt}$$

where

S = Survival rate, typically 10% if 90% deactivation is the goal

k = A species-dependent inactivation rate constant. Measured k values for coronaviruses have been in the range of 0.0025 cm²/µW-sec to 0.0038 cm²/µW-sec (0.25 m²/J to 0.38 m²/J)

I = The average irradiance in µW/cm²

t = Time in seconds

Determining the dose "$I \times t$" based on air handler geometry, surface reflectance and residence time is not simple. According to ASHRAE, although calculating the dose "…appears quite simple, its application can be complex (e.g., when calculating the dose received by a microorganism following a tortuous path through a device with spatial variability in irradiance)." See Reference 1, page 62.1.

Vendor A gave us data on plenum dimensions, air temperature, air velocity, average residence time and UV dose, but neither vendor provided detailed dose calculations that relate lamp output at a reference distance to

*We performed this calculation check based on 2 ft (610 mm) clearance between the coil and the end of the plenum, lamp placement centered in this 2 ft (610 mm) clearance, 420 µW lamp output at 3.3 ft (1 m), 500 fpm (2.5 m/s) air velocity at the coil, and a *k* value (species-dependent inactivation rate) of 0.0025 cm²/µW-sec (0.25 m²/J) (low end of the range to be conservative).

total dose mathematically integrated over time and distance derived from geometry, reflectance and velocity. Vendor A told us orally that they use a "rule of thumb" of 15 W/ft^2 to 20 W/ft^2 (162 W/m^2 to 215 W/m^2) of coil area. While this may be a useful number for budgeting purposes, and may be based on coil cleanliness, it does not readily translate to kill rate of the virus.

We performed a calculation check based on one air handler in the Vendor A proposal, using the above survival rate formula. We used manufacturer literature UV intensity data 3.3 ft (1 m) from the lamp, design air velocity, the lamp centered in a 2 ft (610 mm) plenum length and 21 in. (533 mm) lamp spacing. Even at the farthest point from the lamp (1 ft [305 mm]) and worst-case conditions of highest velocity and lowest *k* value, we found that the UV intensity was more than sufficient to achieve the 90% kill rate. We extrapolated this calculation check to both vendors' allowances for lamp intensity and found all allowances to be sufficient.

UVGI lamps can be installed either upstream or downstream of the cooling coils, and there are varying opinions which is better. Downstream installation, as proposed by Vendor A, has the advantages of killing mold and other biological growth on the wetter face of the coil, exposing the lamps to filtered air; the heat added to the airstream is essentially reheat, which will generally result in better humidity control. Upstream installation, as proposed by Vendor B, has the advantage of higher lamp output due to higher temperature.

Cooler air at coil discharge will reduce performance of lamps. Actual ambient temperature must be taken into account, not just peak performance. Vendor B listed temperature and humidity conditions and duct/plenum UV reflectance, but did not describe how these were used in the calculation to get average *I* = irradiance.

Therefore, we recommended that detailed submittals and calculations should be provided prior to installation, showing:

- Actual air handler dimensions;
- Lamp placement in the air handler;
- Lamp output corrections factor for temperature and air velocity, and source of the factors;
- Lamp output correction factor for lamp age and age of lamp assumed;
- Value used for *k* (species inactivation rate) and biological basis for it;

TABLE 2 Sample calculation of annual electric cost for Building 2.

ELECTRICITY COST	$0.1056/kWh
TOTAL WATTS, BUILDING 2 PER VENDOR A PROPOSAL	10,260 W
OPERATION	3,000 Hours/Year
ANNUAL ELECTRIC COST	$3,300 (Lamps Alone)
ADDITIONAL COOLING COP	3 (Estimated Average Including Parasitic Distribution and System Losses)
TOTAL COST	$4,400 (Lamps and Additional Cooling)
ANNUAL COST	$0.0460/ft^2

Electricity cost source: https://www.electricitylocal.com/states/

- Reflectance of air handler surfaces assumed if credit is taken for reflection;
- Any other values used in the calculations; and
- Detailed calculations based on air handler geometry and the other values above.

Maintenance Cost

Prior to contracting for the installation, we recommended that a proposal for system maintenance be procured from the installer(s), including lamp replacement cost based on useful lamp life and hours of operation. Lamp life is on the order of 10,000 hours, and intensity declines toward the end of life. Hours of operation may vary with each air handler.

Table 2 shows a sample calculation for estimated annual electric cost for running in-duct UVGI lamps at Building 2 based on $0.1056/kWh and 3,000 operating hours per year. Since the lamps add heat to the airstream, this adds cost in the cooling-dominated climate of the buildings.

Based on this, the average annual cost of energy for lamps and the air conditioning to counteract heat from the lamps comes to about $0.045/ft^2 ($0.48/m^2) of building area. This is two to four times higher than the estimated operating cost of $0.01/ft^2 to $0.02/ft^2 ($0.11/m^2 to $0.22/m^2) given in the *2019 ASHRAE Handbook—HVAC Applications*[1] based on a similar electricity cost.

Alternate Recommendations

Other ventilation-related actions that are likely to be more cost-effective and have other benefits for indoor air quality, thermal comfort and, in some cases, equipment life and energy efficiency include:

1. Improve filtration to MERV-13 with good edge seals.
2. Check for adequate airflow to each occupied space.

3. Verify outdoor air quantity and recommission outdoor air tracking; install a dedicated minimum outdoor air duct in some air handlers.

4. Increase outdoor airflow, even as high as double the code-required minimum, with the precaution that overall capacity and humidity control need to be addressed.

5. Recommission equipment, control sequences and settings to improve control of ventilation, thermal comfort and humidity.

In focusing on ventilation actions, we did not cover other issues of building operation outside our areas of expertise, including cleaning, social distancing, mask-wearing policies, signage, etc. Of course, much occupant and visitor behavior is beyond the control of anyone except the individuals involved.

Upper-Room UVGI

In-duct UVGI and the recommendations above depend on clean or disinfected air distributed from a central air handler. The benefits of all these are inherently limited by the quantity of air distribution to the room. An option that interrupts the transmission path *within* the room is upper-room UVGI, which the owner may wish to consider in high-risk occupancies.

The *2019 ASHRAE Handbook—HVAC Applications* (Reference 1, page 62.5) describes spaces appropriate for upper-room UVGI as "…congregate spaces, where unknown and potentially infected persons may share the same space with uninfected persons (e.g., a medical waiting room or a homeless shelter)." One might reasonably extend the application to spaces such as prisons, extended care facilities and waiting rooms for any public services.

In this application, UV fixtures are placed high in the room, typically 7 ft (2 m) above the floor, where they will not harm occupants, yet will irradiate and deactivate respiratory aerosols brought there by air currents, either natural or induced. The *2019 ASHRAE Handbook* lists research from the 1930s to recent years demonstrating the benefits of this technique. The benefit of upper-room UVGI is offset by installation cost, which is reported to be greater than in-duct.

Summary

Installation and operating costs of in-duct UVGI in this case study were higher than those in the *2019 ASHRAE Handbook* by factors of five to nine and by two to four, respectively. When rules of thumb are used for proposing UVGI installations, detailed submittals should be provided showing lamp layout, air handler and duct geometry and resulting irradiance time to demonstrate that the kill rate will be achieved. Prior to installing UVGI, the full benefit of basic ventilation and filtration should be verified by recommissioning of systems.

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References

1. *2019 ASHRAE Handbook—HVAC Applications*, Chap. 62 "Ultraviolet Air and Surface Treatment."

2. ANSI/ASHRAE Standard 185.2-2020, *Method of Testing Ultraviolet Lamps for Use in HVAC&R Units or Air Ducts to Inactivate Microorganisms on Irradiated Surfaces.* ■