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# Assessing Germicidal Ultraviolet Systems

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Building managers face the complex challenge of selecting technologies or strategies to reduce airborne pathogen transmission using ASHRAE Standard 241-2023, *Control of Infectious Aerosols*, or guidelines.[1,2] Data on their effectiveness, energy-efficiency and cost can inform manager's selections. In-room germicidal ultraviolet (GUV) systems are increasingly being considered; this study assesses their contributions to equivalent clean airflow per person (ECAi) goals in an office building and an elementary school.

## Background

In-room GUV systems have a history of efficacy and are recognized by Standard 241-2023, but questions remain regarding their suitability for specific space types, cost and their contributions to equivalent clean airflow per person (cfm/p) for infection risk mitigation (ECAi).

Two types of in-room GUV systems exist: 1) upper-room (UR) GUV, which irradiates a volume above occupants' heads using a 254 nm low-pressure mercury source (LPM) or a 265 nm to 285 nm LED, and 2) whole-room (WR) GUV systems (or far UV-C), which emit 222 nm radiation throughout the occupied room. GUV can also be installed in-duct or in the air-handling unit to reduce biofouling or disinfect recirculated air. Here, we report on GUV installations in two buildings, the Space Needle's new headquarters in Seattle and an elementary school in Grants Pass, Ore.

The first site in this study is the Space Needle's new headquarters, which was completed in 2024. Variable refrigerant flow (VRF) fan coils provide space conditioning, and a dedicated outdoor air system (DOAS) with energy recovery provides ventilation. Initial design goals included providing a minimum of six air changes per hour with outdoor air, but the resulting peak heating load would have required an expensive-to-operate, high-capacity heating coil. So, the design team pivoted to explore more cost-effective air cleaning strategies. These strategies included in-duct MERV 13 filters at the fan coils; LPM in-duct GUV for recirculated air; LED upper-room GUV in open offices, meeting rooms and the break area; and whole-room

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**TABLE 1** Summary of selected space characteristics. §

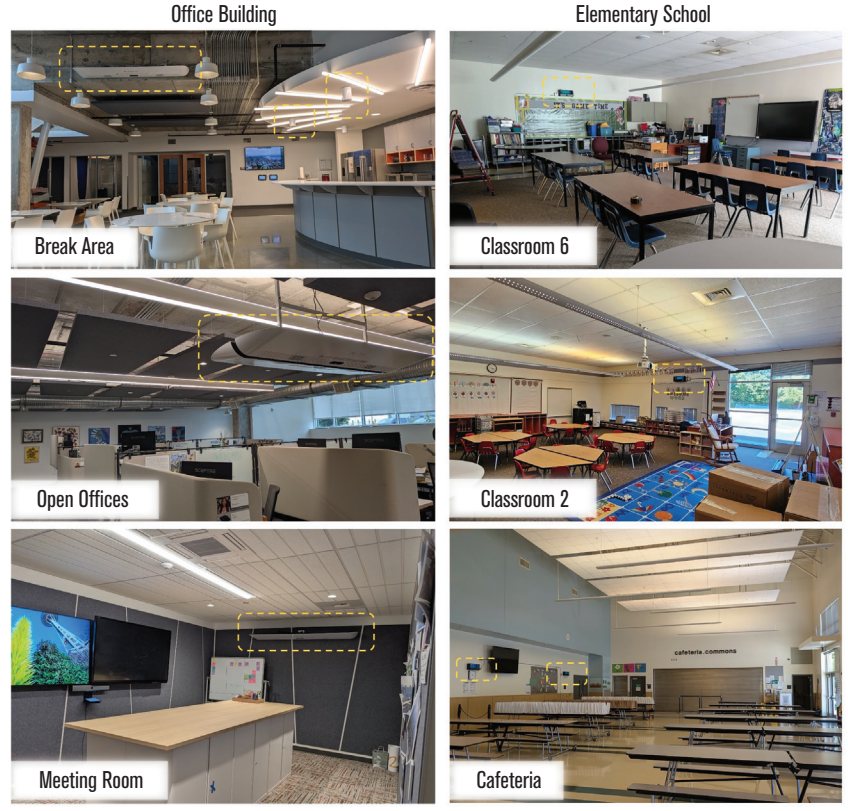
| BUILDING | SPACE | AREA ($ft^2$) | CEILING HEIGHT (ft) | IN-DUCT FILTER MERV RATING | IN-DUCT GUV | IN-ROOM GUV AND PACS | VOLUME ($ft^3$) | FRACTION OF ROOM HEIGHT IRRADIATED‡ | DESIGN OCCUPANCY (PEOPLE) |
|---|---|---|---|---|---|---|---|---|---|
| Office | Break area (dining and kitchen) | 1,134 | 8.5 – 12.5 | 13 | Yes | 1 LED UR and 4 WR | 6,304 for UR; 1,968 for WR | 16% for UR; 90% for WR | 29 |
| | Meeting room | 245 | 8.2 | 13 | No | 1 LED UR | 2,001 | 14% | 12 |
| | Open offices | 3,014 | 9.9 | 13 | Yes | 2 LED UR | 19,772* | 14% | 15 |
| School | Classroom 6 | 937 | 10.0 | 10 | No | 1 LPM UR | 9,370 | 28% | 24 |
| | Classroom 2 | 968 | 10.0 | 10 | No | 1 LPM UR and 1 PAC | 9,680 | 27% | 24 |
| | Cafeteria | 2,662 | 23.5 – 34 | 10 | No | 5 LPM UR and 1 PAC | 79,903 | 44% | 266 |

* Excludes areas that do not receive GUV; this volume was used in Equation 2.
‡ The fraction of room irradiated was from the bottom of the GUV fixture to the first physical obstacles, e.g., the drop ceiling.
§ UR and WR stand for upper-room and whole-room germicidal ultraviolet, respectively.

GUV in lounges and the break area.

The second site is an elementary school completed in 1996. In response to the COVID-19 pandemic, the school district deployed portable air cleaners (PACs), but noise from the selected models disrupted classroom activities. The school district transitioned to LPM upper-room GUV luminaires installed in classrooms, cafeterias and gyms at multiple schools. The school has multiple-zone variable air volume (VAV) air-handling units (AHUs) serving classrooms, where each classroom is one zone with a VAV terminal unit. The gym and cafeteria each have their own constant volume AHU. All AHUs have airside economizer capabilities and can provide up to 100% outdoor air when weather conditions are favorable; minimum ventilation settings are used otherwise.

**FIGURE 1** Six spaces selected for this study in the office building and the elementary school. The GUV luminaires are outlined in yellow in each picture.




Three spaces were selected for study in each building (*Table 1* and *Figure 1*). In each space, we evaluated equivalent clean airflow rate ($V_{ECAi}$ in cfm) accounting for contributions from ventilation and from in-duct and in-room systems ($V_{ACS}$). Assuming design occupancy per ASHRAE Standard 62.1-2022, estimated equivalent clean airflow per person (ECAi in cfm/person) values were compared to ECAi goals from ASHRAE Standard 241-2023 (30 cfm/p [15 L/s·p] for office spaces, 40 cfm/p [20 L/s·p] in the classroom and 60 cfm/p [30 L/s·p] in the cafeteria).[3] We also compared two methods for estimating ECAi from in-room GUV systems, assessed UV-C exposure safety, measured ozone concentration because far UVC with wavelengths below 242 nm is known to generate ozone and evaluated GUV equipment costs. Field data for both buildings was collected in summer 2025.

**TABLE 2** The susceptibility (*K* value) of the three selected challenge agents to different UV irradiation wavelengths. To convert to $cm^2/mJ$, multiply values by 10.

| CHALLENGE AGENT | *K* ($m^2/J$) | | | REFERENCE |
|---|---|---|---|---|
| | FAR UV-C 222 nm | LPM 254 nm | LED 268 nm | |
| MS2 (lower *K* value) | 0.078† | 0.038 | 0.041† | 5, 6 |
| MS2 (higher *K* value) | 0.575 | 0.346 | 0.400 | 7 |
| Mtb | - | 0.480 | - | 8 |
| HCoV-OC43 | 1.426 | 0.647 | 0.799* | 9 |

† Extrapolated using the *K* value at 254 nm from Walker and Ko5 and spectral response from Beck et al.[6]
* This *K* value was for 263 nm LED.

## Evaluation Methods

### Ventilation, In-Duct Filtration and GUV

To assess the clean airflow from ventilation and in-duct filtration, we collected and estimated minimum and maximum supply and outdoor airflow rates from HVAC design documents, air balance testing results and building automation systems. Unless otherwise noted, we used the minimum outdoor air ventilation rates as a worst-case scenario. For in-duct filters, we used the infectious aerosol removal efficiency from Standard 241-2023 based on the nominal MERV rating and the recirculated (supply minus outdoor) airflow rate.

For in-duct and in-room GUV, bioaerosol test results were not available, so we used methods that require the *K* value. This value describes a challenge agent susceptibility to UV-C, with a higher value indicating higher susceptibility. In this study, we selected three challenge agents with different susceptibility levels including the bacteriophage MS2, *mycobacterium tuberculosis* (Mtb) and human coronavirus (HCoV-OC43). MS2 is included to align with Standard 241-2023, and Mtb is included for comparison with proposed ASHRAE Guideline 37, *Guidelines for the Application of Upper-Air (Upper Room) Ultraviolet Germicidal (UV-C) Devices to Control the Transmission of Airborne Pathogens*, for upper-room GUV. One caveat is that the susceptibility of Mtb is not available for far UV-C or LED wavelengths. Note that there is considerable variability in reported *K* values spanning over an order of magnitude for MS2.[4] Given that the primary results consider MS2, we chose two *K* values for MS2 (lower and higher estimates) to convey uncertainty. Both MS2 *K* values were included in a recent literature review; the higher *K* value for MS2 and that for HCoV-OC43 align with the proposed values (*Table 2*).[4]

For in-duct GUV at the offices, the manufacturer estimated a dose ($D_{uv}$) of 3.5 $mJ/cm^2$ (two 60 W lamps for the break area and two 95 W lamps for the open office; other details were not available). Based on this dose and the *K* values of MS2 and HCoV-OC43 for UV-C 254 nm, a single-pass inactivation efficiency of 74% to 100% was calculated for MS2 and 100% for HCoV-OC43 using *Equation 1*.[10]

$$\eta = 1 - e^{-kD_{uv}} \quad (1)$$

These estimates likely represent a best-case scenario and should be interpreted with caution because the dose was not field verified; variations in air speed, temperature and humidity are known to affect the delivered dose.[10] Furthermore, because the in-duct GUV was downstream of high-efficiency filters, its contribution to total ECAi was relatively limited. The inactivation efficiency ($\eta$) is multiplied by the volumetric rate of recirculated air (excluding the air cleaning system equivalent clean airflow rate, $V_{ACS}$, from the upstream filter) to calculate $V_{ACS}$ for in-duct GUV.

### In-Room GUV and PACs

Standard 241-2023 defines $V_{ACS}$ of in-room GUV systems according to Appendix A chamber test results using bacteriophage MS2, a surrogate for airborne pathogens. Appendix A test results were not available for the GUV luminaires installed at the school and offices, so we used an in-situ method to estimate $V_{ACS}$ using radiometric measurements, i.e., measurements of incident UV-C energy. This method can capture room-specific influences on effectiveness that a lab-based chamber test cannot, like the influence of GUV mounting height, position in the room and reflectivity of materials; it also provides validation of UV-C output.

$V_{ACS}$ can be calculated for a well-mixed room using *Equation 2* with the average fluence rate ($f_{avg}$ in $W/m^2$), the *K* value ($m^2/J$), the fraction of room height irradiated by UV-C ($h_{uv}$) to room height ($h_r$), and volume (*V* in $ft^3$) (*Table 1*).[11] The constant 60 is a unit conversion factor. We acknowledge that the air in evaluated spaces may not be well-mixed; the second measurement method based on

an air tracer helps address this limitation.

$$V_{ACS} = \left(f_{avg} \times k \times \frac{h_{uv}}{h_r} \times V\right) \times 60 \quad (2)$$

Fluence rate represents the rate of UV-C energy falling on a particle from all directions. Fluence rate can be estimated by measuring the incident UV-C energy at a point from multiple directions, i.e., irradiance. We used a method that required seven irradiance ($I$) measurements for each point (*Equation 3*).[12,13] Using a tetrahedron as an approximation, measurements normal to the faces of a tetrahedron can be collected (one aimed at zenith and three side measurements). To reduce sensitivity to the orientation of the tetrahedron, another set of side measurements was collected after rotating the tetrahedron 60° around its vertical axis. The two sets of side measurements were then averaged and added to the zenith measurement.

$$\text{Fluence rate} = I_{Zenith} + \frac{[(I_{0°} + I_{120°} + I_{240°}) + (I_{60°} + I_{180°} + I_{300°})]}{2} \quad (3)$$

In each space, fluence rate was estimated on a grid of points covering either the entire area or a sampled portion, scaled to floor area (e.g., 4 ft × 4 ft [1 m × 1 m] in the classrooms and 10 ft × 10 ft [3 m × 3 m] in the cafeteria). These measurements were collected using a radiometer. For the whole-room kitchen area in the office building, readings were taken at two heights, while for the upper-room, measurements were conducted at one or two heights depending on the luminaire's mounting height.

In the school, a second method was used to estimate $V_{ACS}$ of GUV based on DNA-tagged tracer tests. DNA UV-sensitive and UV-insensitive particles were aerosolized at the same time, with PACs off, enabling separate calculations of GUV inactivation and background decay due to physical removal mechanisms, e.g. ventilation and deposition.[14] Tracer test results were scaled to MS2 based on the ratio of $\Delta eACH_{MS2}/\Delta eACH_{tracer}$ from chamber tests; this ratio was 2.63. meaning that MS2 was more sensitive to UV than the tracer.[14] For PACs, $V_{ACS}$ was calculated based on AHAM AC-1 test results and particle size distribution per Standard 241-2023.

### UV-C Exposure and Ozone Concentration

The American Conference of Governmental Industrial Hygienists (ACGIH) establishes recommended limits for the amount of GUV that a healthy, working-age person can safely be exposed to without adverse health effects to skin or eyes.[15] These limits are dependent on the UV-C spectrum and assumed exposure duration. In each space, we measured the spectral irradiance distribution using a spectroradiometer and measured irradiance using a radiometer at a standing height 6.2 ft (1.9 m) to check for "hot spots" where the irradiance might exceed the time-weighted average irradiance limit. The measurement locations were selected to represent typical occupant positions. Ozone concentration measurements were collected. Corresponding outdoor ozone concentrations were retrieved from a nearby weather station.[16]

### GUV Equipment and Installation Cost

Installed costs (equipment and labor) were collected from the GUV manufacturer for the school and from the facility manager for the office building. They were then normalized by each space's floor area and by the radiometrically-estimated ECAi from the GUV. Installation costs and $V_{ACS}$ are specific to those two sites, product manufacturers and installation teams and not broadly applicable, but provide a point of reference for future analyses.

## Results

### ECAi in The Office Building

*Figure 2* shows the ECAi contributions from technologies and measures considering MS2 or HCoV-OC43. Considering MS2 at the two $K$ values, the Standard 241-2023 goal ECAi of 30 cfm/p [15 L/s·p] was met and in some cases far exceeded in all spaces. The provided ECAi in the open office was about 6 to 10 times the goal (174 cfm/p to 295 cfm/p [82 L/s·p to 139 L/s·p]), mostly due to the GUV and a high airflow rate. Upper-room GUV provided 13 cfm/p to 125 cfm/p (6.1 L/s·p to 59 L/s·p) in the open office ($f_{avg}$ = 2.9 µW/cm$^2$). In the meeting room, the upper-room GUV ($f_{avg}$ = 8.9 µW/cm$^2$) added between 5 cfm/p and 51 cfm/p (2.5 L/s·p to 24 L/s·p) to the 29 cfm/p (14 L/s·p) provided by the HVAC system.

The break area had a unique combination of two types of GUV systems with upper-room GUV in the dining space and four whole-room GUV luminaires in the kitchen area. The whole-room luminaires in the kitchen

**FIGURE 2** The equivalent clean airflow (ECAi) provided by each technology or strategy for the three spaces in the office building assuming design occupancy. Total provided ECAi for each space is shown at top of each bar stack. In-room GUV contributions were determined using radiometric testing and susceptibility of MS2 or HCoV-OC43, whereas in-duct GUV contributions were calculated using Equation 1.

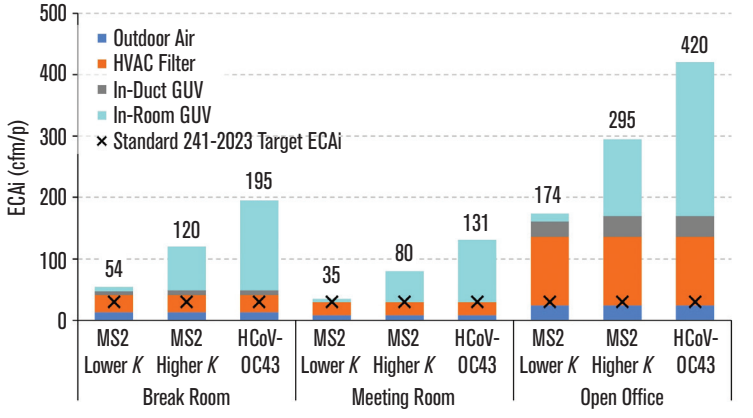
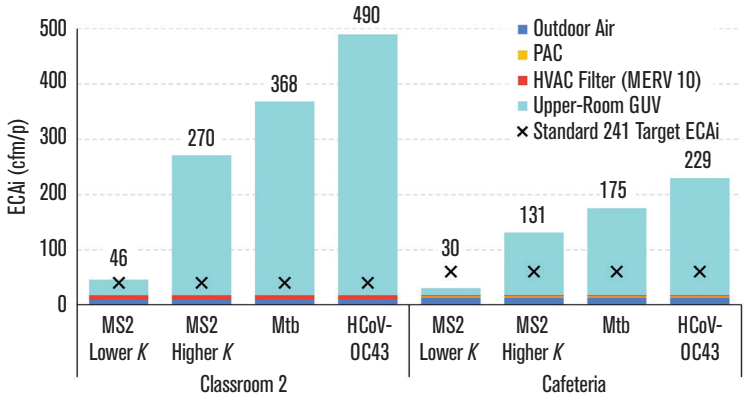



**FIGURE 3** The equivalent clean airflow (ECAi) provided by each technology or strategy at the elementary school. Total provided ECAi for each space is shown at top of each bar stack. GUV contributions were determined using radiometric testing and susceptibility values shown in Table 2.




area provided $V_{ACS}$ of 31 cfm to 227 cfm (15 L/s to 107 L/s), which is lower than the 189 cfm to 1,847 cfm (89.2 L/s to 872 L/s) provided by the upper-room in the dining area. This is likely due to the lower average fluence rate provided by the whole-room system ($f_{avg}$ = 0.4 µW/cm$^2$) compared to upper-room ($f_{avg}$ = 7.6 µW/cm$^2$).

## ECAi in the Elementary School

*Figure 3* shows the ECAi for Classroom 2 and the cafeteria considering three challenge agents with varying susceptibility to UV-C assuming minimum ventilation and a hypothetical 47% filtration efficiency for MERV 10. The 47% filter credit is based on a proposed revision for Standard 241-2023. Considering the lower *K* value of MS2, only Classroom 2 met the goal, whereas if we consider the higher *K* value of MS2, both spaces far exceed their goals. Of the 46 cfm/p to 270 cfm/p (21 L/s·p to 127 L/s·p) achieved in Classroom 2, 61% to 93% (28 cfm/p to 252 cfm/p [13 L/s·p to 119 L/s·p]) were provided by the upper-room GUV system ($f_{avg}$ = 11.3 µW/cm$^2$). Classroom 2 had a PAC, but without an AHAM AC-1 test, so its contribution to ECAi was not considered.

Radiometric measurements revealed that Classroom 6 had a significantly depreciated GUV lamp beyond its end of life and in need of replacement. For this reason, results for Classroom 6 are not included. The classrooms' minimum ventilation rates are about half of what Standard 62.1-2022 specifies.

The school cafeteria had an ECAi of 30 cfm/p to 131 cfm/p (14 L/s to 62 L/s); the upper-room GUV accounted for 41% to 86% of the total ECAi, providing 12 cfm/p to 113 cfm/p (6 L/s·p to 53 L/s·p) ($f_{avg}$ = 10.0 µW/cm$^2$). The 540 cfm (255 L/s) PAC provided only 2 cfm/p (0.9 L/s·p) due to the high design occupancy in this space.

## Comparisons by Test Method and Challenge Agent

To compare the estimated $V_{ACS}$ between the radiometric and DNA-tagged tracer methods, one common variable to keep consistent is the *K* value. The *K* value of MS2 was not directly measured in the experiment that determined the ratio of MS2 to DNA tracer sensitivity.[14] Based on the ratio and the reported D90 of 292 J/m$^2$ ($K$ = 0.008 m$^2$/J) for the DNA tracer, we estimated the *K* value for MS2 in that study as 0.021 m$^2$/J.[14] This *K* value is similar to the lower *K* value of 0.038 m$^2$/J used in this article.

As anticipated, the radiometric method with a lower *K* value produces $V_{ACS}$ results that align with the DNA tracer test in Classroom 2, but are roughly half those of the tracer test in the cafeteria (*Table 3*). The difference in the cafeteria might be due to a difference in air mixing; the radiometric method assumes that the air is well-mixed and does not account for obstacles that might impede air movement like the suspended ceiling panels (~9 ft [3 m] below the roof) in the cafeteria, which likely

affected air mixing (*Figure 1*). The tracer method can account for airflow patterns but used a limited number of sampling points and relies on chamber testing to scale tracer decay results to MS2. More testing is needed in spaces with and without physical obstructions in-room to pinpoint the source of discrepancy between the two measurement methods.

### UV-C Exposure and Ozone Concentration

Irradiance measurements were collected in all spaces except Classroom 2. None of the measurements exceeded the ACGIH limits for typical exposure durations in these spaces. Mean irradiances were 0.1 μW/cm$^2$ for upper-room spaces and 1.4 μW/cm$^2$ in the office building kitchen area (whole-room GUV); this is 11% of the corresponding ACGIH limits.

Far UV-C luminaires were used in one of the six spaces evaluated. However, we measured the ozone concentration in all spaces during radiometric data collection, which lasted several hours in each space. In the space with whole-room luminaires (office building kitchen area), ozone concentration did not exceed 5 ppb, well below the NIOSH exposure limit of 100 ppb. On measurement days, outdoor ozone concentrations near the office building were 16 ppb to 31 ppb.[16] The low indoor levels compared to outdoor levels indicate there is not a significant ozone generation source indoors.

**TABLE 3** Equivalent clean airflow from upper-room GUV in the school Classroom 2 and cafeteria assessed using two in-situ methods. A lower *K* value is included for the radiometric method to assess alignment with the tracer method.

| SPACE | METHOD 1: RADIOMETRIC MEASUREMENTS | | METHOD 2: DNA TRACER TEST |
|---|---|---|---|
| | *K* value (m$^2$/J) | $V_{ACS}$ for MS2 (cfm) | $V_{ACS}$ for MS2 (cfm) |
| Classroom 2 | 0.038 | 665 | 742 |
| | 0.346 | 6,055 | |
| Cafeteria | 0.038 | 3,307 | 7,351 |
| | 0.346 | 30,115 | |

### GUV Equipment and Installation Cost

*Table 4* shows the cost normalized by floor area and by $V_{ACS}$ for each space. The normalized cost varies with GUV installation design (number of luminaires and the space area), manufacturer, luminaire model and assumed challenge agent. Classroom 6 does not represent normal use conditions because of the depreciated UV lamp and is not included in this analysis.

The difference in the two *K* values considered for MS2 translates to cost estimates per cfm that vary by about an order of magnitude. The costs considering HCoV-OC43 or Mtb are only 5% to 8% of those for MS2 with the lower *K* value and 49% to 67% of those for MS2 with the higher *K* value. For comparison to PACs, we estimated the average first cost per ECAi of 36 consumer products with $V_{ACS}$ between 63 cfm (30 L/s) and 524 cfm (247 L/s) to be $1.4 per cfm ($2.97 per L/s). Assuming MS2 with the higher *K* value, in-room GUV first costs are lower than PACs in Classroom 2 and the cafeteria and higher than PACs in the office building.

The costs of the office installations are higher because the office used an UR product that uses an adjustable LED source and internet connectivity with remote monitoring, compared to the legacy LPM source used in the school. The office break area also included whole-room GUV with a krypton-excimer source that has a higher cost per watt than the upper-room LPM technology. Lastly, the layout of the three spaces in the office building limited mounting options, reducing the fraction of room irradiated (*Table 1*), and in turn $V_{ACS}$.

## Conclusions

**GUV effectiveness.** The GUV systems provided considerable contributions toward ECAi goals while remaining well below UV-C exposure limits. Assuming

**TABLE 4** GUV equipment and installation cost. ECAi and $V_{ACS}$ are based on the radiometric test. Space area and number of GUV luminaires are in Table 1.

| BUILDING AND GUV VENDOR | SPACE | ECAi FROM IN-ROOM GUV FOR MS2 (HIGHER *K*) (cfm/p) | $/ft$^2$ | $/cfm | | | |
|---|---|---|---|---|---|---|---|
| | | | | MS2 LOWER *K* | MS2 HIGHER *K* | Mtb | HCoV-OC43 |
| Office, GUV Vendor 1 | Break area | 72 | $19.8 | $102.3 | $10.9 | - | $5.3 |
| | Meeting room | 51 | $24.9 | $97.9 | $10.0 | - | $5.0 |
| | Open offices | 125 | $4.0 | $63.2 | $6.5 | - | $3.2 |
| Elementary school, GUV Vendor 2 | Classroom 2 | 252 | $1.8 | $2.6 | $0.3 | $0.2 | $0.2 |
| | Cafeteria | 113 | $3.2 | $2.6 | $0.3 | $0.2 | $0.2 |

MS2, in-room GUV contributions ranged from 51 cfm/p to 125 cfm/p (24 L/s·p to 59 L/s·p) in the office building. In the school, contributions were estimated at 113 cfm/p to 252 cfm/p (53 L/s·p to 119 L/s·p) using the radiometric method and 28 cfm/p to 31 cfm/p (13 L/s·p to 15 L/s·p) using the tracer method.

**Methods.** The assumed *K* value directly affects estimated effectiveness and cost per cfm for GUV technologies. A need exists for reference *K* values that can be consistently used across studies. This will make it easier to compare in chamber and in-situ methods for estimating $V_{ACS}$ from GUV.

**GUV performance optimization.** The mounting height and placement of GUV systems affected the estimated equivalent clean airflow. This suggests that these systems should be incorporated into early design to maximize the benefits and reduce costs.

**In-situ testing for GUV technologies.** In-situ testing for GUV system effectiveness can capture performance factors like mounting height, position, airflow patterns and UV-C output, which are not accounted for by a chamber test method. A radiometric test method can also help monitor performance as UV-C output declines without visible cues.

**Maintenance of GUV systems.** Replacing depreciated lamps in GUV luminaires is crucial. Adding in-line run-time loggers can assist building managers to monitor use and plan maintenance and would be a useful feature to add to GUV equipment. Occupancy sensors or smart switches can optimize operation, reducing lamp change frequency and energy use.

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