INVITATION TO SUBMIT A RESEARCH PROPOSAL ON AN ASHRAE RESEARCH PROJECT

1873-TRP, Upper-Air Ultraviolet Germicidal Irradiation (UVGI) for Tall Spaces (re-bid)

Attached is a Request-for-Proposal (RFP) for a project dealing with a subject in which you, or your institution have expressed interest. Should you decide not to submit a proposal, please circulate it to any colleague who might have interest in this subject.

Sponsoring Committee: TC 2.9 Ultraviolet Air and Surface Treatment
Co-sponsored by: TC 9.6 Healthcare Facilities

Budget Range: $315,000 may be more or less as determined by value of proposal and competing proposals.

Scheduled Project Start Date: **September 1, 2025,** or later.

All proposals must be received at ASHRAE Headquarters by 8:00 AM, EDT, May 30, 2025. NO EXCEPTIONS, NO EXTENSIONS. Electronic copies must be sent to rpbids@ashrae.org. Electronic signatures must be scanned and added to the file before submitting. The submission title line should read: 1873-TRP, Upper-Air Ultraviolet Germicidal Irradiation (UVGI) for Tall Spaces, and *"Bidding Institutions Name"* (electronic pdf format, ASHRAE's server will accept up to 10MB)

If you have questions concerning the Project, we suggest you contact one of the individuals listed below:

For Technical Matters
Technical Contact
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American Ultraviolet
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For Administrative or Procedural Matters:
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Contractors intending to submit a proposal should notify, by mail or e-mail, the Research Administrator by May 1st, 2025 in order that any late or additional information on the RFP may be furnished to them prior to the bid due date.

All proposals must be submitted electronically. Electronic submissions require a PDF file containing the complete proposal preceded by signed copies of the two forms listed below in the order listed below. **ALL electronic proposals are to be sent to rpbids@ashrae.org.**

All other correspondence must be sent to ddaniel@ashrae.org. Hardcopy submissions are not permitted. **In all cases, the proposal must be submitted to ASHRAE by 8:00 AM, EDT, May 30, 2025.**
NO EXCEPTIONS, NO EXTENSIONS.

The following forms (Application for Grant of Funds and the Additional Information form have been combined) must accompany the proposal:

(1) ASHRAE Application for Grant of Funds (electronic signature required) and
(2) Additional Information for Contractors (electronic signature required) ASHRAE Application for Grant of Funds (signed) and

ASHRAE reserves the right to reject any or all bids.

State of the Art (Background)

Upper-Room Germicidal Ultraviolet (UR-GUV), also known as Upper-Room or Upper-Air Ultraviolet Germicidal Irradiation (UVGI), is an effective means to reduce or eliminate the transmission of airborne infectious diseases, including influenza, human coronaviruses (like SARS-CoV-2 that caused the recent COVID-19 pandemic), and tuberculosis (the most deadly infectious disease in the world). While performance efficacy is unquestioned, design approaches are challenging. Typical UR-GUV fixtures are installed a minimum of 7 feet above the floor. They incorporate horizontal baffles to direct the UV energy across the upper irradiated zone while limiting direct or reflected UV exposures to people in the lower occupied zone. The result is usually a relatively-narrow horizontal GUV irradiated zone directly above the occupied space. Air mixing from mechanical ventilation, human thermal plumes, and human activities ensures that infectious aerosols move into the irradiated zone where they are inactivated and no longer capable of causing disease. In 2009, the CDC's National Institute for Occupational Safety and Health (NIOSH) published *Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings*. That guidance resulted from a 2-year research effort to evaluate the ability of a well-designed and thoroughly characterized upper-air UVGI system to inactivate airborne mycobacteria (a surrogate for the bacteria that causes tuberculosis). The NIOSH guidelines recommend a UV irradiance zone, as uniform as possible, with an average UV irradiance of 30–50 $\mu W/cm^2$ applied across the zone's horizontal cross-section. One limitation of the NIOSH guidance is that, while there are industry rules of thumb that are used on the front end of the design process, system designers cannot easily determine the actual average UV irradiance until after fixture selection and installation. This uncertainty leads to some ineffective and/or inefficient (i.e. over-designed) systems. Recently, researchers proposed a new strategy for upper-air system design based on total room volume, as opposed to horizontal room cross-section. Mphaphlele et al. (2015) stated that properly designed upper-air systems should provide a total UV fixture output of 15–20 mW/m^3 of total room volume, as calculated by a commercially-available computer-assisted design program modified for UV use. A more recent, yet unpublished study by the same research group, saw the same effectiveness from a total UV fixture output of 12 mW/m^3 of total room volume, so this lower UV dose requirement has replaced the older 15–20 mW/m^3 recommendation (Nardell 2021). This new volume-based design strategy proved effective in the study from which it originated. Its adoption into practice has been limited and less researched. It likely works well in spaces with typical ceiling heights of 8-10 feet (the study space had a 9-foot ceiling height). However, there are questions about its use in tall spaces (there are some questions about the applicability of the NIOSH guidelines to tall spaces as well). By definition, the volume-based method requires twice as much energy if the height of a given space is doubled. In conclusion, the efficacy of typical UR-GUV systems needs to be evaluated in spaces with different ceiling heights, and when tall ceiling applications exist, simple changes to fixture designs (opening upper quadrant louvers) need to be evaluated to see if they can provide cost-free efficacy improvements, especially if the improvements will compensate for any changes in efficiency resulting from the tall ceilings.

Justification and Value to ASHRAE

Research is necessary to address issues precluding consensus design guidelines for upper-air GUV systems installed in tall spaces. Mphaphlele's 12 mW/m^3 volume-based approach to system design is met with apprehension from some system designers due to perceived penalties on initial equipment and energy costs when the strategy is applied to tall spaces. Under this room volume design strategy, a given room requires a certain number of UV fixtures to adequately dose the space with UV energy. However, that same room footprint, with the ceiling height doubled, requires twice as many fixtures and twice the energy use, despite the fact that the source generation and the occupant density in the occupied zone remains the same. There is significant debate on whether these additional fixtures are needed in tall spaces, or alternatively, whether some other modification to current fixture design (at the same energy consumption) is appropriate to compensate for tall spaces. It is entirely possible that systems designed for ceiling heights of 10 feet are sufficiently effective when applied to tall spaces without design modification. The prevailing argument against the room volume method is that if a 12-inch horizontal irradiated zone with an appropriate irradiance level adequately protects room occupants in a room with 10-foot ceilings, that same irradiated zone should remain protective to occupants in that same room with higher ceilings. After all, the volume of the occupied space and the associated pathogen generation rate is unchanged. Also, a room with a higher ceiling has the added benefit of increased dilution based on volume alone, and any viable airborne contaminants existing above the irradiated zone in a tall space would have to travel back through the irradiated zone prior to potentially exposing occupants. While this prevailing hypothesis seems plausible, no published research studies have investigated the concentration of viable microorganisms in the occupied zone for upper-air systems and the effect that ceiling height has on the system performance.

As stated in the 2022 ASHRAE Positions Document on Infectious Aerosols, ASHRAE supports research that advances the knowledge base of indoor air management strategies aimed to reduce occupant exposure to infectious aerosols. The Infectious Aerosols positions document went on to specifically cite UVGI as one of those strategies. ASHRAE also strives to provide scientifically robust design and operational guidance. In the area of Upper-Room GUV systems, GPC-37 is currently working to finalize the initial complete draft of *Guidelines for the Application of Upper-Air (Upper Room) Ultraviolet Germicidal (UV-C) Devices to Control the Transmission of Airborne Pathogens.* However, when it comes to UR-GUV, a key knowledge gap exists regarding the proper design for spaces with ceilings higher than 10 feet. The knowledge gained from this proposed research will fill that knowledge gap, making ASHRAE guidance stronger, increasing scientific validity, and resulting in more cost-effective and energy-efficient UR-GUV systems. In turn, these improved systems will better protect people in the occupied zone from exposure to infectious aerosols.

This project will serve to blend ASHRAE, NIOSH and evolving industry guidance into overall best practice, which will likely become the new industry "standard" for UR-GUV design and installation (Guideline 37). The results will also provide useful information for inclusion in the HVAC Systems and Equipment Handbook, Chapter 17: Ultraviolet Lamp Systems as well as in the HVAC Applications Handbook, Chapter 62: Ultraviolet Air and Surface Treatment.

Objectives

The goal of this research is for ASHRAE to develop science-based design guidance for UR-GUV systems in spaces with tall ceilings. This research will determine if spaces with tall ceilings require more ultraviolet energy in the irradiated zone than spaces with typical 8-10 feet ceilings. If tall spaces do require more UV energy for adequate inactivation of airborne microorganisms, this project will also determine whether simply opening the upper louvers of typical UR-GUV fixtures can provide the added energy required, without the need to increase the number of fixtures, increase fixture wattage, or otherwise require special accommodations to design (or redesign) UR-GUV systems due simply to increased ceiling height. The ultimate determination will be based on the ability of an UR-GUV system to control the concentration of viable surrogate microorganisms in the occupied zone (below 7 feet) in a test room with different ceiling heights. The findings will scientifically validate a unified design method for UR-GUV systems in tall spaces, which will be included in Guideline 37 - *Guidelines for the Application of Upper-Air (Upper Room) Ultraviolet Germicidal (UV-C) Devices to Control the Transmission of Airborne Pathogens*, currently being developed. Once published, Guideline 37 will become the de facto standard for UR-GUV systems in the United States and many parts of the world. It will also represent the first document with scientifically validated design guidance specific to UR-GUV systems installed in tall spaces.

Scope:

Research Test Room

A research test room having approximately 150-250 square feet of floor space and an adjustable ceiling height will be established. The baseline condition is a ceiling height of 9 feet±1 foot (low position). A high ceiling position of at least 15 feet must be achievable (heights up to 20 feet are encouraged). Also, a middle ceiling position between the low and high position must be tested. The minimum distance between any two ceiling height settings should be no less than 3 feet. The room must have a ceiling fan centered in the space. The fan should be mounted with the bottom of the fan no more than 1 foot below the low ceiling height, and the fan should remain in that position, regardless of the ceiling height. The fan will be operated at the same rpm and directional rotation setting during all testing. A means to maintain constant temperature (±2°F) and relative humidity (±5%) within the test room must be incorporated into the research protocol and temperature and humidity must be kept as consistent as possible throughout all tests. The test room must also include a means to clean the air inside the room before/after each test. This can be accomplished with a mechanical ventilation system equipped with HEPA filters attached to the test room or by using portable HEPA filtration units. Ventilation of the test room is not necessary during testing.

Upper-Room GUV (UR-GUV) System for Testing

Using the Centers for Disease Control and Prevention's (CDC's) National Institute for Occupational Safety and Health (NIOSH) guidelines, *Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings*, an appropriate UR-GUV system will be designed and selected based

on the low position ceiling height in the test room. This UR-GUV system should provide a uniform irradiance zone of 30–50 $\mu W/cm^2$, which should be confirmed with radiometer measurements, chemical actinometry, computer modeling, or a combination of methods. Radiometry measurements should also be conducted to ensure the occupied zone (measured at 6 feet off the floor) does not exceed a 0.2 $\mu W/cm^2$ maximum irradiance using an 80° field-of-view inlet cone on the radiometer sensor. When selecting individual UV fixtures, the investigators should work with fixture manufacturers to ensure that fixture louvers can be adjusted or replaced with other louver systems to allow more UV energy to escape the upper quadrant of the fixture as the ceiling height is increased. Once installed in the test room, all fixtures shall be operated for a minimum of a 100-hour burn-in time prior to any testing.

Test Room Configurations for Testing

A minimum of five room configurations should be tested as part of this research. Each configuration should be tested a minimum of six times against each surrogate microorganism (three tests with the UR-GUV system off and three tests with the UR-GUV system on). The five minimum configurations are:

1.) Baseline: Ceiling at low position. Ceiling fan no more than 1 foot below the low ceiling position. UR-GUV system designed according to the NIOSH guidelines (described above) and installed properly.
2.) Ceiling at the middle position. Ceiling fan in the same position as condition 1 above. Same UR-GUV system mounted at the same location as in condition 1.
3.) Ceiling at the high position. Ceiling fan in the same position as condition 1 above. Same UR-GUV system mounted at the same location as in condition 1.
4.) Same test as condition 2 above, but with same UV fixtures in the same position and operated using the same fixture wattage output, but the fixture louvers opened (or changed) to allow as much UV energy from the fixtures while maintaining a maximum irradiance of 0.2 $\mu W/cm^2$ in the occupied zone.
5.) Same test as condition 3 above, but with same UV fixtures in the same position, and operated using the same fixture wattage output but the fixtures louvers opened (or changed) to allow as much UV energy from the fixtures while maintaining a maximum irradiance of 0.2 $\mu W/cm^2$ in the occupied zone.

Note that documented access to research facilities compatible with the above requirements will be considered during the proposal evaluation phase.

Test configurations 1-3 above should answer the primary research question: Does the height of the space above the UV irradiated zone matter regarding effective UR-GUV system design? If that answer turns out to be yes, then conditions 4-5 will address the question of whether the same UV system, when applied to tall spaces, can be adjusted to provide enhanced performance equal or beyond that of a traditional louvered fixture applied to the configuration 1 baseline condition.

Once each of the 5 test conditions are established, UV measurements are required to determine that UV irradiance levels at 6 feet would be safe for room occupants (e.g., resulting in exposures below the NIOSH Recommended Exposure Limit). If measurements show that the levels of UV in the occupied space are unsafe, adjustments shall be made to the fixtures until safe levels are obtained under all test conditions. It is anticipated that going from the baseline condition to conditions 2 and 3 will not result in unsafe levels of UV in the occupied zone. Still, measurements should be taken and documented to confirm this. UV measurements in the irradiated zone shall also be taken to map the UV irradiance levels in three dimensions starting from the bottom of the UV fixtures up through the ceiling height. These measurements can be taken with radiometers or chemical actinometry.

Microbiological Testing

Microbiological testing should be conducted with at least two surrogate organisms to represent typical airborne pathogens. The same strain of each organism should be used for all testing and recognized microbiological methods should be used for all culture preparations. The organisms chosen should be safe and easy to work with, and robust with respect to natural decay during prolonged environmental testing. *Bacillus subtilis* spores are recommended as a more UV-resistant organism for this reason. Enterobacteria phage MS2 is similarly recommended as a viral surrogate, given the viral particle relevance to the COVID-19 pandemic and the fact that testing with MS2 is required for GUV systems to be used under ASHRAE Standard 241: *Control of Infectious Aerosols*. However, these organisms are only recommendations and investigators may choose any two organisms if they adequately justify the decisions. Testing with each microorganism will be done separately. All microbiological testing will be conducted

using aerosol generation and sampling methods similar to those described by Miller et al. (2002) for the Constant Generation Method Protocol (and associated sections). Regardless of the method used to aerosolize airborne microorganisms, the aerosol generation rate and/or the aerosol generation time shall be adjusted to keep the airborne concentration of organisms as consistent as possible across all test conditions as the ceiling height changes. Particle counters or some other method of determining total aerosol concentrations during each test shall be used to account for individual concentration differences between tests. The proposed protocol should indicate how variations in the generation rate/generation time between test conditions will be determined and documented. Additionally, known and unknown experimental variation should be accounted for in the statistical design approach to the experimental protocol, in order to account for multiple test conditions conducted across extended time periods and compared to a documented base-line performance efficiency. The final reported result for each organism at each room condition shall be the effectiveness of the GUV system under the evaluated test condition (see Equation 1 in the Miller report). Appropriate statistical analyses of the results at each condition and across conditions shall be included. The Decay Method Protocol in the Miller report is not required as part of this project, but testing using that protocol can be included at the discretion of the investigator.

To successfully meet the goals of this project following the objectives stated earlier, 6 tasks are defined below. The investigator may rearrange these tasks for better testing flow in their proposal but must include all of the goals and milestones to allow the PMS to monitor the progress of the project.

Task 1: Validating test facility compatibility with project needs.
The chosen investigator will have been required to identify their approach towards an intended test facility as part of the proposal and evaluation process. It is anticipated that actual facility upgrades required to meet the requirements of this project may not occur until after proposal selection. This could mean better sealing of the room (including where the ceiling meets the top of the walls after changing the height), the addition of a ceiling fan that can stay no more than 1 foot below the low ceiling position, adding ventilation or portable HEPA filter units to allow for air cleaning between test runs, or installing temperature and humidity monitoring stations. The PMS should be notified if any obstacles are found that would change the timeline of the project or influence the data collection. The PMS will be notified that this process is complete by a short report describing the chamber, its capabilities, and how they were documented.

Task 2: Designing, procuring and installing the UR-GUV system in the test room, as well as procuring the 2 surrogate microorganisms to be used for testing.
During this task, the UR-GUV system (with adjustable or replaceable louver systems) will be installed in the test room in the baseline configuration and the lamps will undergo at least a 100-hour burn-in time. UV measurements should be taken and documented in accordance with the proposer's approved research protocol to demonstrate safety in the occupied zone and proper irradiance levels in the UV zone. The microorganisms for testing will also be verified per the project proposal, including ATCC numbers. At this stage, the investigator will document any required deviations or omissions from the project proposal in regard to the method for acquisition of the organisms, methods for cultivating and storing them, procedures for aerosolization, sampling, and enumeration. The investigator will also submit a document validating their intended safety and quality assurance procedures and document any deviations from procedures identified in the project proposal. A short report detailing the configurations and equipment will be prepared and shared with the PMS. The PMS must approve the report before work on Task 3 begins. Submission of this report to the PMS completes Milestone 1.

Task 3: Acquiring all necessary equipment, setting up the test room and microbiological laboratory to run the specific tests, and conducting initial range-finding tests, if necessary.
It is anticipated that appropriate aerosol generation rates and times may require some initial trial-and-error testing. Similarly, sampling methods, laboratory methods, and enumeration techniques may need refinement prior to real testing. The PMS is to be notified via a short report when this task is accomplished, including any difficulties that were encountered, decisions made to overcome the difficulties, and any change requests made to previously agreed-upon procedures or procedures identified as part of the accepted research proposal. Completion of Task 3 indicates that real testing is ready to begin.

Task 4: Running the tests as outlined above.
A minimum of 60 individual tests are required to meet the project goals (5 test configurations x 2 microorganisms x 6 tests per condition [3 tests with UV on and 3 tests with UV off]). Each sample collected during each test shall be

plated in triplicate. The total number of samples and plates will depend on the number of sampling locations in the occupied zone that are deemed necessary by the investigator's proposed research protocol. Care shall be taken, and documented in the research proposal, to adopt appropriate statistical and randomization research procedures as to distinguish between independent and correlated repetitions.

Results shall be shared with the PMS at least quarterly. Revisions to the test plan may be needed if the data do not meet expectations. Any such revisions should obtain prior approval by the PMS in order to achieve successful completion of Research Task 4. Completion of all agreed-upon testing following previously approved protocols and reporting of initial results to the PMS meets the requirements for Task 4 and completes Milestone 2.

Task 5: Analyzing the Data.
Appropriate statistical analyses shall be used to understand the testing results. A short report outlining initial results, and subsequent approval by the PMS, shall satisfy the requirement for Task 5.

Task 6: Reporting the Results.
In addition to the short reports provided previously to the PMS, the investigator will prepare a Final Report on the project, outlining all materials, methods, results, analyses, and conclusions from the work. The Final Report must be presented to the PMS at least one month before the end of the project to allow for PMS input and time for the investigator to revise the document. Submission of the Draft Final Report to the PMS completes Milestone 3.

Submission of the revised Official Final Report completes the project. Additionally, ASHRAE requires publication of a journal article (see below). Details on the journal article and other final reporting requirements are provided in the added ASHRAE section of the TRP. Submission of the Official Final Report and the required journal article complete Milestone 4 and allows final payment.

Deliverables:
Progress, Financial and Final Reports, Technical Paper(s), and Data shall constitute the deliverables ("Deliverables") under this Agreement and shall be provided as follows:

a. Progress and Financial Reports

Progress and Financial Reports, in a form approved by the Society, shall be made to the Society through its Manager of Research and Technical Services at quarterly intervals; specifically on or before each January 1, April 1, June 10, and October 1 of the contract period.

The following deliverables shall be provided to the Project Monitoring Subcommittee (PMS) as described in the Scope/Technical Approach section above, as they are available:

Furthermore, the Institution's Principal Investigator, subject to the Society's approval, shall, during the period of performance and after the Final Report has been submitted, report in person to the sponsoring Technical Committee/Task Group (TC/TG) at the annual and winter meetings, and be available to answer such questions regarding the research as may arise.

b. Final Report

A written report, design guide, or manual, (collectively, "Final Report"), in a form approved by the Society, shall be prepared by the Institution and submitted to the Society's Manager of Research and Technical Services by the end of the Agreement term, containing complete details of all research carried out under this Agreement, including a summary of the control strategy and savings guidelines. Unless otherwise specified, the final draft report shall be furnished, electronically for review by the Society's Project Monitoring Subcommittee (PMS).

Tabulated values for all measurements shall be provided as an appendix to the final report (for measurements which are adjusted by correction factors, also tabulate the corrected results and clearly show the method used for correction).

Following approval by the PMS and the TC/TG, in their sole discretion, final copies of the Final Report will be furnished by the Institution as follows:

-An executive summary in a form suitable for wide distribution to the industry and to the public.
-Two copies; one in PDF format and one in Microsoft Word.

c. *Science & Technology for the Built Environment* or ASHRAE Transactions Technical Papers

One or more papers shall be submitted first to the ASHRAE Manager of Research and Technical Services (MORTS) and then to the "ASHRAE Manuscript Central" website-based manuscript review system in a form and containing such information as designated by the Society suitable for publication. Papers specified as deliverables should be submitted as either Research Papers for HVAC&R Research or Technical Paper(s) for ASHRAE Transactions. Research papers contain generalized results of long-term archival value, whereas technical papers are appropriate for applied research of shorter-term value, ASHRAE Conference papers are not acceptable as deliverables from ASHRAE research projects. The paper(s) shall conform to the instructions posted in "Manuscript Central" for an ASHRAE Transactions Technical or HVAC&R Research papers. The paper title shall contain the research project number (1873-RP) at the end of the title in parentheses, e.g., (1873-RP).

All papers or articles prepared in connection with an ASHRAE research project, which are being submitted for inclusion in any ASHRAE publication, shall be submitted through the Manager of Research and Technical Services first and not to the publication's editor or Program Committee.

d. Data

Data is defined in General Condition VI, "DATA"

e. Project Synopsis

A written synopsis totaling approximately 100 words in length and written for a broad technical audience, which documents 1. Main findings of research project, 2. Why findings are significant, and 3. How the findings benefit ASHRAE membership and/or society in general shall be submitted to the Manager of Research and Technical Services by the end of the Agreement term for publication in ASHRAE Insights

The Society may request the Institution submit a technical article suitable for publication in the Society's ASHRAE JOURNAL. This is considered a voluntary submission and not a Deliverable. Technical articles shall be prepared using dual units; e.g., rational inch-pound with equivalent SI units shown parenthetically. SI usage shall be in accordance with IEEE/ASTM Standard SI-10.

Level of Effort

This project is expected to need 6 PI months and 12 research assistant months.
Expected duration is 18 months with a cost of $315,000.

No.	Proposal Review Criterion	Weighting Factor
1	Contractor's understanding of Work Statement as revealed in proposal.	**15%**
2	Quality of methodology proposed for conducting research.	**25%**
3	Contractor's capability in terms of facilities.	**15%**
4	Qualifications of personnel for this project, including plans to encourage student participation in the research activities (through direct involvement and/or outreach efforts).	**25%**

Project Milestones:

No.	Major Project Completion Milestone	Deadline Month
1	**Submission of Task 1 and 2 reports to PMS**	**5**
2	**Submission of Task 3 and 4 reports to PMS**	**14**
3	**Submission of Task 5 and the Draft Final Report in Task 6 to the PMS for Review**	**17**
4	**Submission of the Official Final Report (and ASHRAE mandated journal article)**	**8**

References

1. ASHRAE [2023]. Ultraviolet air and surface treatment. In: ASHRAE handbook - HVAC applications, Chapter 62. Atlanta, GA: ASHRAE.
2. ASHRAE [2023]. 2019 – 2025 ASHRAE Strategic Plan Midterm Update, Atlanta, GA: ASHRAE.
3. ASHRAE [2022]. ASHRAE Positions on Infectious Aerosols, Atlanta, GA: ASHRAE.
4. ASHRAE [2021]. 2021 ASHRAE Research Strategic Plan, Atlanta, GA: ASHRAE.
5. ASHRAE [2020]. Ultraviolet lamp systems. In: ASHRAE handbook - HVAC systems and equipment, Chapter 17. Atlanta, GA: ASHRAE.
6. Miller SL, Hernandez M, Fennelly K, Martyny J, Macher J, et al. [2002]. Efficacy of ultraviolet irradiation in controlling the spread of tuberculosis. Report to the National Institute for Occupational Safety and Health (NIOSH). NIOSH Contract #200-97-2602. Available at: http://stacks.cdc.gov/view/cdc/11285.
7. Mphaphlele M, Dharmadhikari AS, Jensen PA, et al. [2015]. Institutional tuberculosis transmission. Controlled trial of upper room ultraviolet air disinfection: a basis for new dosing guidelines. American Journal of Respiratory and Critical Care Medicine 192(4):477-484. doi:10.1164/rccm.201501-0060OC.
8. Nardell EA [2021]. Dir disinfection for airborne infection control with a focus on COVID-19: Why germicidal UV is essential. Photochemistry and Photobiology 97:493-497. doi: 10.1111/php.13421.
9. NIOSH [2009]. Environmental control for tuberculosis: Basic upper-room ultraviolet germicidal irradiation guidelines for healthcare settings. DHHS (NIOSH) Publication No. 2009-105. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Available at: https://www.cdc.gov/niosh/docs/2009-105/default.html.