INVITATION TO SUBMIT A RESEARCH PROPOSAL ON AN ASHRAE RESEARCH PROJECT

1936-TRP, Evaluation of relative impact of air change rate (ACR) and airflow patterns on the ventilation performance of indoor spaces

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: MTG.ACR

Budget Range: $400,000 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: 1936-TRP, *Evaluation of relative impact of air change rate (ACR) and airflow patterns on the ventilation performance of indoor 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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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)

Air change rate (ACR) is currently understood as a guiding parameter in the built environment for designing spaces with adequate thermal comfort and air quality under a variety of source and use conditions, including high-performance spaces such as cleanrooms (Behrens et al., 2021). ACR appears throughout HVAC and related fields, including ASHRAE standards (ASHRAE, 2017, 2019). During the COVID-19 pandemic, the U.S. Centers for Disease Control and Prevention employed the ACR to quickly propagate guidance, "5 or more ACH," for protection against the airborne aspects of SARS-CoV-2 (CDC, 2023), and ACRs have been used in designing ventilation for health care facilities for many years (CDC, 2003; WHO, 2009). The concept of ACR is simply the volumetric flow rate delivered to a space normalized to (divided by) the space volume, and complete mixing is implied. In current practice, designing to a level of ventilation performance using ACR is considered appropriate under a ventilation scheme that provides good mixing (Pantelic & Tham, 2012), but deviations from good mixing, where local flow patterns are important exposure determinants, greatly reduce the correlation of ACR and exposure control (Pantelic & Tham, 2013). The convenience offered by the ACR concept pushes its application into less accurate territory, where well-mixed assumptions are not met. Deviations from good mixing are often treated with mixing factors used to over-specify flowrates (ACGIH, 2019). Specific knowledge about source locations is used in zonal approaches (Nicas, 1996), and zonal air distribution can even consider the size distribution of an infectious aerosol (Conlan, 2021). Knowledge of flow patterns and source characteristics reduces the reliance on prescribed flowrate increases that may lead to significant over-design and excess energy use (ASHRAE, 2022). Occupancy is an important consideration when ventilation is meant to control occupant-related contamination, such as airborne infectious disease. Recommended airflow rates can be normalized to occupancy (number of persons) rather than to occupied space volume (ASHRAE, 2023).

The practice of using situational knowledge to improve upon the whole-space dilution concept that underpins much ACR-based design guidance is already somewhat present in HVAC and related fields, but systematic studies are lacking, especially regarding airflow patterns. Airflow patterns can play a critical role in estimating exposure levels of occupants. Good ventilation is still commonly understood as an increased supply of clean air or increased ACR. However, simply increasing the supply may be insufficient to reach specific ventilation goals. Higher local concentrations created by the flow path of contaminants near sources, especially in the breathing zone, can pose a higher exposure risk than is predicted by the bulk mass balance, and this spatial variability plays a vital role in determining risk of infection from airborne pathogens (Khankari, 2016; Mead & Johnson, 2004). There is a notional understanding that contaminant flow path may be influenced by location and type of supply diffusers, supply airflow rates and associated diffuser throws, supply air temperature, size and locations of returns, locations and strengths of heat sources in a room, floor layout (including the location and size furniture and other obstructions to airflow) and, importantly, on the strength, location, and nature of contaminant sources (Khankari, 2018c). While these notions have not been systematically investigated, some progress has been made.

Current guidance for COVID-19 places more emphasis on air cleaning and dilution strategies including portable air cleaners, enhanced filtration, increased ventilation, ultraviolet air cleaners, and in some cases space pressurization for directional control without much understanding of airflow patterns and resulting flow path of airborne contaminants in indoor spaces.

When the role of airborne aerosols in spreading the COVID-19 disease was still uncertain on July 6 2020a a group of 239 scientists appealed to WHO in an open letter that "beyond any reasonable doubt that viruses are released during exhalation, talking, and coughing in micro-droplets small enough to remain aloft in air and pose a risk of exposure at distances beyond 1 to 2 m from an infected individual"

(Morawska & Milton, 2020). This should not have been surprising because of the incidence of COVID-19 infection that occurred in late January 2020 in a restaurant located in Guangzhou province of China. Studies of the situation in this restaurant indicated that the secondary infections were consistent with a spread pattern representative of exhaled virus-laden aerosols without close contact or fomite contact. It was also concluded that the droplet transmission was prompted by air-conditioned ventilation. The key factor for infection was the direction of the airflow (Li et al., 2021).

In Li’s paper, tracer gas measurements and computational fluid dynamics (CFD) simulations were used to predict the spread of fine droplets exhaled by the index patient and the detailed airflow pattern in the Guangzhou restaurant. The high-momentum air-conditioning jet carries the contaminated air at ceiling height. Upon reaching the opposite glass window, the jet bends downward and returns at a lower height. At each table, the rising thermal plumes from warm food and people carry the contaminated air upwards, and the remaining air returns to the air-conditioning unit and forms a recirculation zone or cloud envelope. The formation of a relatively isolated contamination cloud is supported by the measured ethane concentration data. CFD simulations showed good agreement with the epidemiologic evaluations and tracer gas analysis. This study validated the applications CFD for such analyses.

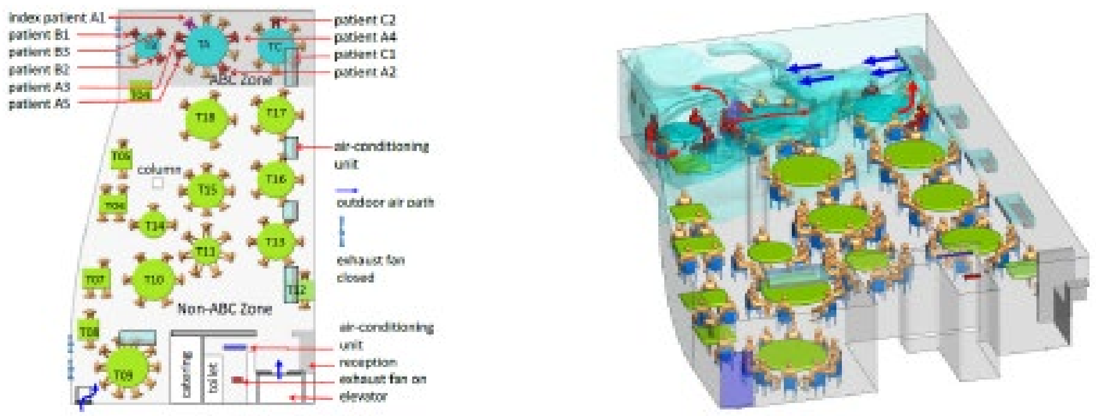

Figure 1: Simulated dispersion of fine droplets exhaled from index Patient A1 which are initially confined within the cloud envelope due to the zoned air-conditioning arrangement. The fine droplets eventuallydisperse into the other zones via air exchange and are eventually removed via the restroom exhaust fan. The ABC zone clearly has a higher concentration of fine droplets than the non-ABC zone. Other infected patients are shown in red and other non-infected in gold color. Only a single human body is used to represent all patrons (Li et al., 2021).

During the Middle Eastern Respiratory Syndrome (MERS) epidemic, a systematic study of the effect of ventilation mode, ventilation rate, and person-to-person distance on person-to-person contaminant transport validated a CFD model with experimental results (Chen et al., 2014). It was shown that stratified air systems including displacement and underfloor air distribution (UFAD) were about 20% better than mixing ventilation in reducing exposure to person-to-person contaminant transport. It further concluded that person-to-person distance is more important than ventilation mode and ventilation rate in controlling person-to-person contaminant transport.

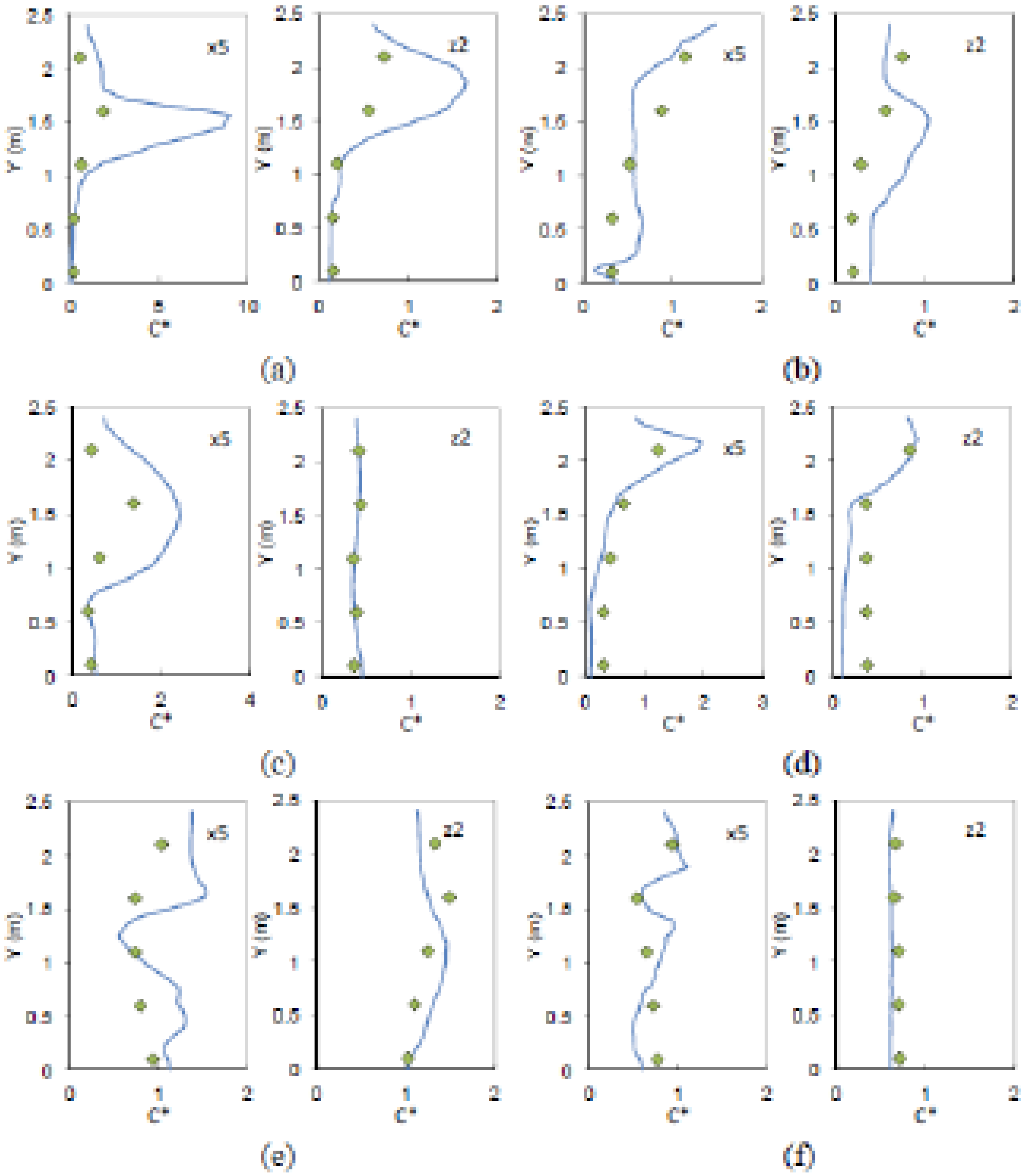

Figure 2. Comparison of the measured and calculated SF6 concentration profiles for (a) UFAD: 3 ACH and 0.5 m person to person distance; (b) UFAD: 3 ACH and 1.1 m distance; (c) UFAD: 6 ACH and 0.5 m distance; (d) UFAD: 6 ACH and 1.1m distance; (e) UFAD: 9 ACH and 0.5 m distance; and (f) UFAD: 9 ACH and 1.1 m distance (Chen et al., 2014).

These studies that have identified air contaminant paths (both detrimental and advantageous) are not referenced here to imply that ACR should be used for ventilation configurations other than mixing. They are cited to show how systematically validated experimental results can agree with CFD simulations, which then indicates CFD can be employed in studying the impact of various complex inter-related design and operating HVAC variables that impact the flow path of airborne contaminants and resulting exposurelevels. Physical testing through experimentation, if possible, requires systematic investigation of one parameter at a time to reveal its impact on a design performance. In addition to the network of numerous sensors, it requires several such careful investigations to obtain statistically significant conclusions. Not only are these efforts time and resource intensive, but sometimes inconclusive due physical limitations of the experimental setup. Often the conclusions are specific to the data collected during the testing. On the other hand, numerical experiments through CFD simulations do not have such restrictions. Several mutually competing variables in complex geometrical configurations can be implemented and studied using CFD analyses. Thus, CFD can evaluate the ability of ACR specifications to achieve ventilation performance goals in various settings, where ACR is apparently a reasonable characterization.

CFD has been used in recent studies to identify flow patterns in existing designs that can be improved to reduce exposures. An important concept in analyzing exposure patterns is Khankari's Spread Index (SI) (Khankari, 2018a). The SI is a CFD based measure of ventilation effectiveness. It is the ratio of the volume of the room occupied by contaminants above a certain target/acceptable concentration to the total volume of the room. Ideally the space ventilation systems should minimize the contaminant concentrations levels below the desired target concentration everywhere in the space and should limit the spread of contaminants above the desirable level. Thus, Spread Index helps in analyzing and quantifying the extent of spread of contaminants in a space above the desirable target concentration. The following three figures describe some relationships of ACR, airflow patterns, and contaminant flow paths.

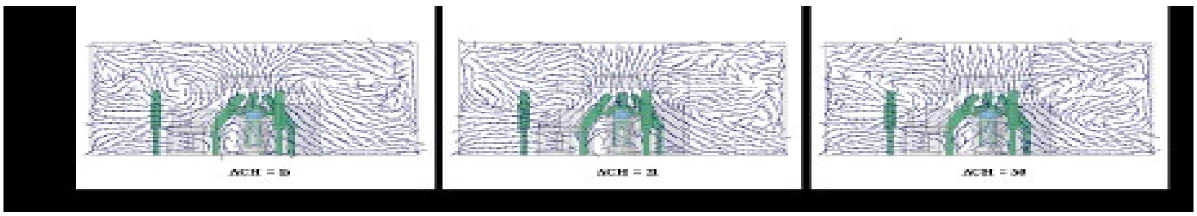

Figure 3: CFD analysis of a typical hospital operating room indicates that air changes per hour (1/h) do not affect the nature of airflow patterns in a room. This analysis further indicated that the resulting flow path of airborne contaminants is also not affected by ACH (Khankari, 2018b).

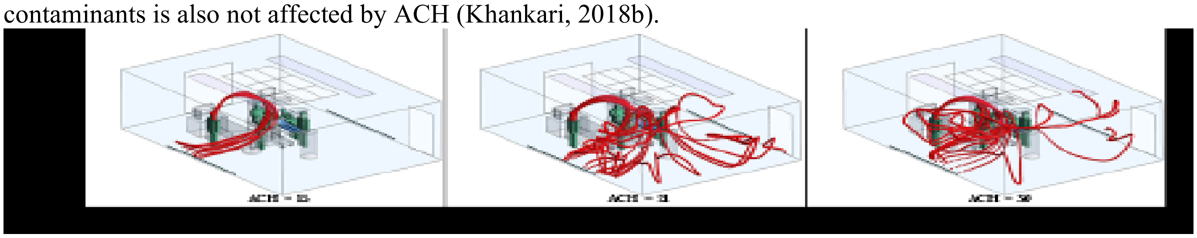

Figure 5: CFD analysis of a typical patient room shows the flow path airborne particles released from the patient's face. This HVAC configuration entrains airborne particles back into the supply air stream which eventually spreads into the entire room. Placement of a return grille right behind the linear supply diffuser over the patient's head (figure b) can potentially provide ready flow path to airborne particles to exit out of the room without significant recirculation and entrainment back into the supply stream (Khankari, 2016).

The preceding discussion of specific, situational knowledge that can be used to evaluate ACR as a performance benchmark underscores the assertion here that the state-of-the-art of ACR, when applied to achieve ventilation goals, is currently ad hoc and essentially anecdotal. Intentional, systematic experiments and CFD simulations involving the notionally important variables would advance the understanding of the strengths and weaknesses of ACR with respect to ventilation performance.

Justification and Value to ASHRAE

The proposed research aims to benefit the HVAC industry, specifically ASHRAE, in the following ways:

- Most ASHRAE ventilation Standards (62, 170, and 241) currently rely on the intuition of industry professionals for setting ventilation airflow rates. This research will provide physics-based guidance to ASHRAE Standards in establishing ventilation flow rate specifications.
- ASHRAE Standards (62, 170, and 241) and guidelines currently specify dilution ventilation rates in terms of air changes per hour, flow rate per person
- (cfm/person), or flow rate per unit area (cfm/sqft), with little or no reference to the requirement for airflow patterns for effective removal of contaminants from the breathing zone. This research aims to offer high-level guidance related to the positioning of supply and returns for effective ventilation.
- Currently, the HVAC industry relies solely on guidance for dilution airflow rates, often leading to high air change rates. This research will demonstrate the importance of HVAC layout, including the selection and placement of supply diffusers and return grilles, to reduce this reliance and achieve effective ventilation. This, in turn, would help reduce carbon emissions from buildings, lower initial costs for HVAC equipment, and decrease subsequent operating costs for building ventilation.

Objectives

The main goal of the proposed research is to evaluate the relative impact of air changes per hour (ACH) and airflow patterns on the ventilation performance in indoor spaces and verify that an optimized HVAC layout can improve the ventilation performance without excessive ACH. Both experimental and computational fluid dynamics (CFD) approaches will be employed to achieve the following specific objectives:

1. Perform in-depth analytical literature review to identify the existing knowledge and the gaps in the understanding of role of ACH and relative impact of airflow patterns.
2. Evaluate the impact of types of supply diffusers, number of diffusers, and their locations on the ventilation performance for various levels of ACH as stated in the test matrix.
3. Evaluate the impact of number and location of exhaust grilles/returns on the ventilation performance as stated in the test matrix.
4. Evaluate the impact of room size on the ventilation performance for certain layouts of supply diffusers and exhaust grilles/returns.
5. Evaluate the impact of supply air temperature on the ventilation performance for a select HVAC layouts.
6. Employ CFD analysis to guide the experimental setup and sampling locations.
7. Validate CFD analysis results with the experimental data for a select set of tests.
8. Employ CFD analysis to extend the test matrix beyond the planned experimental test matrix to evaluate impact of various variables on the ventilation performance.
9. Evaluate relative merit of various metric employed in analyzing the ventilation performance in CFD as well as experimental analysis.
10. Perform experimental data analysis to develop correlations between the HVAC layout and ventilation performance for various ACH.
11. Write a comprehensive report to incorporate analytical literature review, methodologies, and findings, and conclusions of the research.

Scope:

The main goal of the proposed research is to develop an in-depth understanding of the relative impact of air changes per hour (ACH) and airflow patterns on the ventilation performance in indoor spaces and verify that an optimized HVAC layout can improve the ventilation performance without excessive ACH. These objectives will be met by performing Computational Fluid Dynamics (CFD) analyses and experimental verifications for a variety of HVAC layout and operating conditions.

Task1: Analytical Literature Review

A comprehensive review of the literature will be performed to understand the scope and limitations of the existing studies. This task should develop an in-depth analytical report that will include list of all the relevant CFD and experimental studies, lessons learned, the knowledge gap, metrics used to evaluate ventilation performance, and applicability to the proposed research. The analytical literature review should help guide the CFD analyses and experimental investigations.

Task 2: CFD Analysis

CFD Approach

The proposed CFD analyses will predict non-isothermal airflow patterns, temperature distribution, and contaminant (surrogate) distribution. These studies will develop quantitative understanding of the ventilation performance for different scenarios of HVAC layout, air change rates, and supply air temperature as described in the previous section of objectives of the research.

The specific goals of CFD analyses are as follows:

a. Analyze the impact of various HVAC layouts and operating conditions on the performance of ventilation. This will be evaluated by employing various metrics for ventilation effectiveness.
b. Provide guidance to experimental setup and evaluation.
c. Extend the parametric evaluation beyond the experimental test matrix to evaluate impact of levels of various variables which might not be feasible to test during the experimental evaluations.
d. Provide a set of CFD tests for validation and comparison with experimental evaluation.
e. Evaluate relative merit of various metrics employed in analyzing the ventilation performance. If necessary, suggest new metrics for ventilation effectiveness.

FD involves solution and analysis of transport equations of fluid flow, heat transfer, mass transfer, and turbulence. The transport of mass, momentum, energy, and chemical species are governed by a generalized conservation principle that can be described in the form of a general differential equation. A well-validated and widely used general purpose commercial CFD software (Fluent) should be used for these analyses.

Computational Model

The CFD models shall include all major features and obstructions to airflow as represented in the experimental setup. Trivial details which are not important for the airflow analysis can be simplified or neglected. These analyses will be performed for a steady state (snap shot in a time) with non-isothermal and turbulent airflow. The proposed model shall include appropriate supply diffusers and exhaust grilles. Supply air temperature and flow rate shall be specified at the supply grilles/diffusers whereas the exhaust grilles can be assumed to be at a neutral ambient pressure. The buoyancy effect due to heat sources shall be incorporated in the analysis. The surrogate contaminant shall be released at a certain constant rate from a certain location as per the experimental setup. The contaminant transport shall be modeled using Eulerian approach. The ventilation performance shall be analyzed by using various approaches as available in the literature.

The boundary conditions for the supply diffusers shall be modeled as per the guidance in the ASHRAE Research Project. Supply diffusers shall be modeled as per the manufacturers' specifications for the terminal velocity and associated throws. When the discharge velocity profile is available from the manufacturers, it shall be used as inlet velocity profile at the supply locations of the diffusers.

Grid Sensitivity

A good quality computational mesh plays crucial role in the solution convergence and accuracy of the predictions. An appropriate unstructured mesh involving tetrahedral, hexahedral, pyramid, wedge, and polyhedral elements (or a combination of these) shall be employed for the analyses. For a select set of analyses the mesh size shall be varied from course to fine to evaluate the dependency on the mesh size. A set of monitors shall be placed in the model to evaluate the mesh dependency.

Turbulence Models

Similar to the computational mesh can also impact the convergence and accuracy of the CFD predictions. Reynolds-averaged Navier-Stokes (RANS) approach shall be used for the selection of turbulence models. For specific set of analyses three different RANS turbulence model shall be employed to test the sensitivity. In addition to the sensitivity to various computational monitors, experimental data shall be used to test the validity of the turbulence models.

Presentation of CFD Results

After completion of the analysis a written report will be prepared describing computational model, model input, and boundary conditions with the following specific deliverables:

- The computational results shall be presented in the form of color contour, vector, iso-surfaces, and streamlines plots describing distribution of various parameters including temperature, contaminant concentration, air velocity, turbulence intensity, etc.
- Appropriate path lines plots shall be prepared to describe airflow patterns and flow path of contaminants. Whenever appropriate flow animations shall be developed to supplement the path lines plot to show three dimensional airflow patterns.
- Based on the experimental and CFD predictions a detailed cause-and-effect analysis shall be developed to understand the impact of various parameters on the ventilation effectiveness.
- Quantitative indices shall be developed to normalize the impact of various parameters for analytical comparison between various CFD analyses.

Task 3: Experimental Evaluations

The main goal of the experimental evaluations is to develop an understanding between the airflow patterns and ventilation performance for various HVAC layouts and operating conditions as stated in the Table 1. Additionally, experimental evaluations should be used to validate a set of CFD analyses and demonstrate the benefits and limitations of both approaches.

The experimental set-up is crucial to the verification and validation process. The experimental setup should have at least the following requirements:

1. The experimental space should be able to vary the room size as per Table 1. The air distribution system for the room must be reconfigurable. It adapts to fit the various room sizes, the numbers of diffusers and exhaust grills and the types of diffusers. Bidders will indicate how they intend to meet that requirement.
2. The room ceiling should be able to accommodate various locations and number of supply and return locations.
3. The air handler should provide required range of air changes per hour as per Table 1
4. The space should have representative moveable objects to provide obstructions to airflow.
5. The space should have load banks to represent sensible cooling loads
6. The air cooling system should be able to vary the supply air temperature at typical dew points as per Table 1
7. The space should be adequately sealed and insulated to minimize air leaks and heat transfer.
8. Each aspect of the physical room construction should align with the CFD model parameters such as physical dimensions, air temperature, surface temperatures, supply and return register location and performance, physical barriers, and other parameters effecting mass and heat transfer.
9. All test runs should be video recorded. The Test Room shall include windows to allow for external monitoring of experiments and videography of tests.

The experimental measurements should at least meet the following requirements:

1. Airflow patterns is crucial in this research. Experimental procedure to map 3D airflow patterns (directional velocities and magnitude) in the entire experimental space. Bidders will provide detailed description of the instrumentation and plan for the measurements.
2. Ability to release surrogate gaseous contaminant at certain rate, concentration, and temperature. Bidder will provide detailed description of the proposed gaseous surrogate, the injector, and the plan to adjust the release rate.
3. Bidder will provide detailed description of the instrumentation to measure the concentration of the surrogate gas concentration at various locations in the breathing plane and at the supply and exhaust locations.
4. Instrumentation should be able to record temperature, relative humidity, turbulence intensities, and concentration of surrogate gaseous contaminants
5. An external data collection system should be included with workstation(s), monitoring screens, and remote control of air flow rates, temperatures, heat loads, air distribution equipment, etc.
6. The bidder should have appropriate data and statistical analysis software

The experimental procedure should meet at least the following requirements:

1. Ability to attain steady- state conditions in the space. The space should be allowed to attain a steady state before recording the test.
2. Should be able to perform at least 400 tests to analyze the parameters listed in Table 1. Additionally, the bidder will be required to perform sufficient number of initial tests prior to performing the actual experiments to verify the accuracy of measurements. Criteria for starting the actual tests will be set by agreement between researcher and PMS.
3. Bidder should be able to demonstrate repeatability of each test at least for three times.
4. Should be able to purge and record the background concentrations of other contaminants in the space.
5. Bidder shall describe and demonstrate a detailed procedure for calibration of various instruments.
6. Should be able to record appropriate parameters at required locations to compute and assess the ventilation performance.
7. Use appropriate CFD analyses to design of the experiments.
8. Experimental space should be free from any occupants during the tests.

Task 4: CFD Validation

This task involves validation of a few CFD simulations with the experimental results. A set of experimental tests will be selected to validate the accuracy of the predictions of CFD models. The validation process should meet at least the following requirements

1. The experimental measurements including airflow patterns, air velocities, turbulence intensities, temperature distribution, gaseous contaminant concentrations, etc. will be compared with the CFD predictions.
2. Diffuser throws and velocity profiles at the diffuser will be carefully recorded to use as boundary conditions for the CFD models.
3. During the validation process the sensitivity of boundary conditions, computational mesh, and turbulence models can also be tested.
4. Bidder should be able to perform several CFD simulations to test sensitivity of these parameters.
5. Bidder may be required to repeat the tests to reassure the accuracy of the measurements.
6. Relative error between the experimental data and CFD predictions shall be explained and justified.
7. Validated CFD models with appropriate settings for the mesh, turbulence model and boundary conditions shall be employed for further CFD explorations.

Task 5: Data Analysis:

This is an important task that will provide deep insights into the experimental findings. Bidder should be able to perform multivariable statistical analysis for the collected data. Statistical correlations should be developed between several dependent variables and ventilation performance metrics. Both qualitative and quantitative trends should be developed from the experimental data and those should be compared against the trends from the CFD analyses.

Task 6: Report Preparation:

After successful completion of CFD analyses, experimental evaluation, validation, and data analysis a comprehensive report should be prepared. The report should include a detailed analytical literature review. A detailed description of CFD models, experimental setup, and the experimental procedure. The validation with CFD results and statistical correlation should presented and explained with critical review. Finally, a list of conclusions and future research should be included in the report.

Table 1: Proposed Test Matrix

WS-1936 Tests matrix		
Physical Settings		
Room Sizes (Feet)	10 x 10, 10 x 20, 20 x 30	
Room Height (Feet)	9	
Diffusers and Return grilles locations	3 different locations per room size, one test having returns on low wall	
Movable obstacles in room	Potential movable partitions at every 200 sq-ft or blocks that could cause obstruction to airflow in the room	
Diffusers types		
Square 4 ways		ACR 3, 4, 6, 8
Round/square high induction		ACR 6, 8, 10, 15
2 x 4 perforated laminars		ACR 6, 8, 10, 15, 20
System operational conditions		
ACR	3, 4, 6, 8, 10, 15, 20, as per diffuser types	
Supply Temp (°F)	55, 75, Loads needed in the room to simulate occupation	
Contaminant	1 airborne gaseous contaminant	
Contaminants sources locations	One location in breathing zone, Minimize directional velocity of the contaminant diffuser	
Measurements		
Measurements	Temperature, air velocity, air direction and contaminants concentration at each sampling points.	
Sampling locations	At every 40 sq-ft in the breathing zone, minimum 10 per room, and at the return	
HVAC System characteristics		
VAV system that could provide the required ACR (+/- 2 000 CFM) and varying temperature from 55°F to Isothermal		
100% outside air to avoid contaminant re-entrainment in the supplied air to the room		
Airflow measuring station in the supply and the return		
Ducted supplied and returned air.		
Location of diffusers as per manufacturer recommendation.		
Cooling loads in the rooms (+/- 12 kW Heating load to create cooling need and 55°F supply temperature)		

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 (1936-RP) at the end of the title in parentheses, e.g., (1936-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

Project cost: $400,000 (ASHRAE Research: $315,000 Industry cofounding: $85,000)
Please see attached support letters from co-founding organizations.
Project duration: 36 months

Project Milestones:

No.	Major Project Completion Milestone	Deadline Month
1	**Literature review** **DELIVERABLES,** but not limited to: After completion of the analysis a written report will be prepared describing computational model, model input, and boundary conditions with the following specific deliverables: • The computational results shall be presented in the form of color contour, vector, iso-surfaces, and streamlines plots describing distribution of various parameters including temperature.	3
2	**Testing facility set-up and CFD model development** **DELIVERABLES,** but not limited to: After completion of the analysis a written report will be prepared describing computational model, model input, and boundary conditions with the following specific deliverables: • The computational results shall be presented in the form of color contour, vector, iso-surfaces, and streamlines plots describing distribution of various parameters including temperature, contaminant concentration, air velocity, turbulence intensity, etc. • Appropriate path lines plots shall be prepared to describe airflow patterns and flow path of contaminants. Whenever appropriate flow animations shall be developed to supplement the path lines plot to show three dimensional airflow patterns. • Based on the experimental and CFD predictions a detailed cause-and-effect analysis shall be developed to understand the impact of various parameters on the ventilation effectiveness. • Quantitative indices shall be developed to normalize the impact of various parameters for analytical comparison between various CFD analysis.	6

3	**Initial lab test and comparison with CFD simulation** **DELIVERABLES,** but not limited to: The report of this milestone shall include: The experimental procedure should meet at least the following requirements: 1. Ability to attain steady- state conditions in the space. The space should be allowed to attain a steady state before recording the test. 2. Should be able to perform at least 400 tests to analyze the parameters listed in Table 1. Additionally, the bidder will be required to perform sufficient number of initial tests prior to performing the actual experiments to verify the accuracy of measurements. Criteria for starting the actual tests will be set by agreement between researcher and PMS. 3. Bidder should be able to demonstrate repeatability of each test at least for three times. 4. Should be able to purge and record the background concentrations of other contaminants in the space. 5. Bidder shall describe and demonstrate a detailed procedure for calibration of various instruments. 6. Should be able to record appropriate parameters at required locations to compute and assess the ventilation performance. 7. Use appropriate CFD analyses to design of the experiments. 8. Experimental space should be free from any occupants during the tests. The validation report should include at least the following requirements 1. The experimental measurements including airflow patterns, air velocities, turbulence intensities, temperature distribution, gaseous contaminant concentrations, etc. will be compared with the CFD predictions. 2. Diffuser throws and velocity profiles at the diffuser will be carefully recorded to use as boundary conditions for the CFD models. 3. During the validation process the sensitivity of boundary conditions, computational mesh, and turbulence models can also be tested. 4. Bidder should be able to perform several CFD simulations to test sensitivity of these parameters. 5. Bidder may be required to repeat the tests to reassure the accuracy of the measurements. 6. Relative error between the experimental data and CFD predictions shall be explained and justified. 7. Validated CFD models with appropriate settings for the mesh, turbulence model and boundary conditions shall be employed for further CFD explorations.	**9**
4	**Room 10x10 lab tests and CFD analysis** **DELIVERABLES:** A report as for milestone 3 specific to this particular lab dimension	**13**
5	**Room 10x20 tests and CFD analysis** **DELIVERABLES:** A report as for milestone 3 specific to this particular lab dimension	**17**
6	**Room 10x30 tests and CFD analysis** **DELIVERABLES:** A report as for milestone 3 specific to this particular lab dimension	**21**
7	**Statistical results analysis** **DELIVERABLES:** Report presenting multivariable statistical analysis for the collected data. Statistical correlations should be developed between several dependent variables and ventilation performance metrics.	**24**
8	**Extended CFD analysis** **DELIVERABLES:** Report presenting both qualitative and quantitative trends from the experimental data and those should be compared against the trends from the CFD analysis.	**30**
9	**Draft report**	**33**
10	**Final report**	**36**

Proposal Evaluation Criteria
Proposals submitted to ASHRAE for this project should include the following minimum information:

Criteria: No.	Proposal Review Criterion	Weighting Factor
1	Contractor's understanding of Work Statement	**15%**
2	Qualification of personnel Expertise of Principal investigator in this type of research Experience of the person responsible of CFD simulations Experience of team members Time commitment of the principal investigator	**30%**
3	Contractor's capability in term of facilities and instrumentation Test facility available and set-up Software licenses – CFD and statistical Computer hardware	**30%**
4	Probability of meeting the objectives of the research Detailed work plan Risk analysis Proposed project schedule Management plan quality Team management planned	**15%**
5	Performance of contractor on prior ASHRAE Projects (No penalty for new contractor)	**5%**
6	Students involvement	**5%**

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