INVITATION TO SUBMIT A RESEARCH PROPOSAL ON AN ASHRAE RESEARCH PROJECT

1835-TRP, “Characterizing the Performance of Induced Flow Stacks”

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 9.10, Laboratory Systems
Co-sponsored by: TC 4.3, Ventilation Requirements & Infiltration and TC 5.1, Fans

Budget Range: $245,000 may be more or less as determined by value of proposal and competing proposals.

Scheduled Project Start Date: September 1, 2020 or later.

All proposals must be received at ASHRAE Headquarters by 8:00 AM, EDT, May 15, 2020. 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 1835-TRP, “Characterizing the Performance of Induced Flow Stacks”, 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
Brad Cochran
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Contractors intending to submit a proposal should so notify, by mail or e-mail, the Manager of Research and Technical Services, (MORTS) by May 4, 2020 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.

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 reserves the right to reject any or all bids.
**State of the Art (Background)**

Induced flow stacks have been on the market for over 20 years and are used extensively for laboratory exhaust systems as well as kitchen, loading dock, emergency generator, and other emission sources that may have toxic or odorous effluents. While there is a wide range of configurations for these types of fans from various manufacturers, they commonly include an outlet nozzle that is contained within a wind band. It is hypothesized that due to the shape of the nozzles and wind bands and the relative short distance between the top of the nozzle and top of the wind band, that the combine induced air flow and nozzle air flow may not have sufficient opportunity to become well-mixed into a fully developed flow field by the time it exits to the atmosphere at the top of the wind band.

The current testing protocol for these fans are either AMCA Standard 210 (AMCA, 2016), which can be used to measure the total volume flow out of the nozzle, or AMCA Standard 260 (AMCA, 2007) which is designed to measure the total volume flow rate out of the top of the wind band. Neither of these test standards are designed to evaluate the characteristics (i.e., velocity distribution) of the air flow exiting the top of the fan or at the top of the wind band; nor does AMCA 260 address the impacts of a cross-wind on the characteristics or quantities of the induced air flow entering the base of the wind band.

Isyumov and Tanaka (1979) researched plume behavior as a function of the shape of the velocity distribution out of the top of the stack through a series of wind tunnel-based dispersion modeling tests. Their research, which focused primarily on the difference between a fully developed laminar velocity profile and a fully developed turbulent velocity profile, found that the shape of the profile had a dramatic impact on the subsequent plume behavior. They reported that a laminar exhaust profile (parabolic) may have a maximum exit velocity that is 60% greater than a fully developed turbulent exhaust profile (top hat) and an exit momentum that is 33% greater. It is theorized that the difference in exit momentum between the transitioning exhaust profile from an induced flow stack and a fully developed turbulent flow stack could be even more pronounced.

Most current numerical dispersion models (ASHRAE, 2015; EPA, 2004; Turner, 1970) utilize the Briggs plume rise formulas (Briggs, 1984), either directly or indirectly. The Briggs plume rise equations were developed based on observations of plume rise from industrial sized stacks. The effluent from the stacks included in the study were of sufficient height as to allow for the formation of a fully developed turbulent flow profile prior exiting out of the top of the stack.

Similarly, physical modeling of exhaust stacks requires either designing the model to ensure that the flow is fully developed and turbulent based on physical length of the tube and Reynolds number, or the use of trips located inside the tube to create the appropriate outlet conditions (Snyder, 1981). Currently, the plume rise is calculated or simulated assuming that an induced flow type of exhaust has a uniform velocity distribution at the top of the wind band. If this is not the case, and the results of this research project indicate that the velocity profile has a significant impact on the performance of the plume, current numerical and wind tunnel simulations could be incorrectly predicting the plume rise from these stacks; potentially resulting in an either unsafe design, incorrect fan specification, or excessive energy consumption.

**Objective**

The objective of the proposed research is to evaluate the plume performance from various types of induced flow stacks with non-uniform velocity profiles in terms of the downwind plume rise and plume spread. These results will be compared with the plume performance from a conventional exhaust stack with a fully developed velocity profile at the exit of the stack operating in the same environment. Plume rise and plume spread measurements at several downwind distances will be obtained and evaluated to determine whether or not there is a statistical difference between the plumes from induced flow stacks and those from a conventional stack and if they align with values obtained from the ASHRAE dispersion model.

If the results indicate that there is not a statistically significant difference between the induced flow exhaust stack plume behavior (plume rise and spread vs. the stack height wind speed) and those from a conventional exhaust
stack, then the existing dispersion models can continue to be used with confidence that the simulations are accurately predicting the induced flow stack performance. The results will be included in upcoming versions of the ASHRAE Handbook – HVAC Applications “Building Air Intakes and Exhaust Designs”; ASHRAE Handbook – HVAC Systems and Equipment “Fans”; ASHRAE Handbook – Fundamentals “Air Flow Around Buildings”; and in the ASHRAE Laboratory Design Guide. If the results indicate that there is a statistically significant difference, the results will also be published in the aforementioned ASHRAE Handbooks and Design Guide. It will also provide impetus for a follow-on research project, which may be coordinated with AMCA, to develop a methodology and/or ASHRAE testing standard that can be used to characterize all exhaust fans where the exit of the exhaust is not fully developed turbulent flow, for AMCA certification.

Either way, the objective of the research project is to better understand the plume behavior from inducted flow fans and determine whether or not they can be properly simulated with current dispersion models in order to accurately define safe and energy efficient exhaust systems.

**Scope:**
The scope of work for characterizing the plume performance from induced flow stacks comprises of two types of tests. The first test is designed to characterize the shape of the velocity profile just below the top of the wind band. The second test involves measuring the plume height and lateral and vertical spread of the plume downwind of the stack and comparing these results to a fully developed exhaust flow stack operating in the same environment and to calculated values from the ASHRAE dispersion model. All testing should take place in an open field that is void of obstacles that could influence of air flow characteristics within the measurement field.

**Exhaust Fan Selection**
All testing should be conducted on at least 5 different induced flow exhaust fans from at least 3 different fan manufacturers. In addition, testing should also be conducted with a conventional fan (a non-induced type fan) with at least five diameters of straight round stack above the top of the fan, to be used as the benchmark. The fans should be selected with roughly the same operating parameters in terms of static pressure, volume flow rate and exit velocities through the nozzle (velocities and volume flow rates through the top of the wind band may vary depending upon the shape of the wind band). Results will be normalized by the exit momentum, so an exact match is not necessary. All fans included in the research project should be AMCA tested for the volume flow rate through the nozzle and wind band (AMCA 210/ASHRAE 51 and AMCA 260) prior to arriving on site. The recommendation is to test fans with an inlet flow rate of approximately 20,000 cfm (9.4 m3/s) with a nozzle velocity of between 4,000 fpm (20 m/s) and 6,000 fpm (30 m/s) at full flow. As a minimum, the fans should be sized for 15,000 cfm (7 m3/s) and 4,000 fpm (20 m/s) at full flow.

The selection of the induced flow fans should attempt to represent the widest variety of nozzle and wind band configurations currently on the market. The final selection of fans will need to be approved by the PMS before proceeding with any testing.

**Field Site Requirements**
All testing should take place in an open field environment. The site should be void of any structure, other than the test bench and other data acquisition equipment, that can influence the air flow characteristics within the measurement field. The site should be a minimum of 250 ft (76.2 m) in length and 100 ft (30.5 m) in width (see Figure 1), aligned with the predominant wind direction. A grade school or practice football field is a good example of a potential site. There should be no structures within 10 structure heights upwind of the site and within 5 structure heights crosswind of the site. The site should have minimal elevation change (< 10 ft (3.1 m)) and contain vegetation no greater than 3 ft (1 m) tall.
**Test Bench**
A test bench should be designed such that the fans can be mounted on the test bench so that the top of the wind band/stack is consistent for all six fans (5 induced flow stacks and 1 conventional stack) and at the same elevation as the anemometer. The test bench should be mounted along the centerline of the field site perpendicular to the predominant wind direction and at least 3 stack heights upwind of the leading edge of the test site. The bench can be an open frame construction or enclosed box structure. It should allow for air to be drawn into the fan from either a side louver or a bottom louver location. Ductwork leading into the exhaust manifold should follow the fan manufacturer’s recommendations for size and location of elbows from the entrance of the fan. The supply duct should be equipped with an adjustable damper that allows the inlet static pressure to be set and measured so that the fans are operating at the pre-defined position along their fan curve. Measurements of inlet static pressure, motor frequency/fan speed, and fan power should be obtained and compared against published AMCA certified fan curves to confirm the inlet volume flow rate.

**Weather Station**
The test site should be equipped with a weather station to measure the local wind speed, wind direction, ambient temperature, and barometric pressure, as well as lateral, vertical and longitudinal rms wind speed (i.e. turbulence intensity). A 3-D anemometer should be installed so that it is at the same elevation as the top of the wind band of the exhaust fans and perpendicular to the fan for the predominant wind direction for the site. While the use of a sonic anemometer is recommended. A cup and vane or a propeller type anemometer is acceptable but the device should be fully calibrated before any testing is started and again at the completion of all testing. If there is a discrepancy between the pre- and post-test calibrations, a time based pro-rated correction factor should be applied to all data. If the discrepancy is more than 10%, the results will not be considered valid. Therefore, if a cup and vane or propeller type anemometer is used, it may be prudent to either use two anemometers, or to regularly spot check the calibration. The sonic anemometer does not require pre- or post-test calibration, however, the alignment and the proper selection of wind velocity units (mph, m/s, or knots) should be verified.

The ambient temperature and barometric pressure can be measured anywhere within the test site, following standard guidelines for proper placement.

**Characterization Testing**

**Data Collection**
Characterization testing should be performed on each of the exhaust fans to measure the velocity profile just below the exit of the top of the wind band. Velocity profile measurements for each fan should be obtained with at 5 or more exit velocity ratios (the ratio of the nozzle velocity to the approaching wind speed at the top of the stack) ranging between 0.5 to 5.0. These ratios can be achieved by either conducting the measurements within a range of
volume flow rates/exit velocities out of the nozzle under constant approach wind speeds, with a constant volume flow rate/exit velocity out of the nozzle under a range of approach wind speeds, or a combination of both. Velocity measurements should be taken by traversing across the top of the wind band using the log-Tchebycheff method, as described in ANSI/ASHRAE Standard 111 (2017). The testing should include a sufficient number of samples at each velocity ratio to provide a sample variance at each measurement location that is no greater than 10% of the sample mean.

The profile should be obtained with a measuring device, such as a multi-holed probe, that can provide the velocity vector (i.e., velocity magnitude and direction) at each measurement location. In lieu of this, velocity profile measurements can be obtained at multiple planes (at least three additional planes) below the top of the wind band in order to characterize the transition of the velocity profile through the wind band. Care must be taken to make sure that the measuring device does not alter the air flow trajectory within the nozzle. The total blockage area created by the measuring device should be less than 1 percent of cross-sectional area of the wind band at the measurement plane and no more than 5% at any other plane within the wind band.

For a stack with a uniform discharge fan nozzle, the velocity profile should be characterized by at least three velocity transverses across each plane of the wind band (60 degrees apart), with six velocity measurements per travers, as shown in Figure 3.

![Figure 2. Sampling points for traversing the top of the wind band for an induced flow stack with a uniform nozzle using the log-Tchebycheff method.](image)

For an induced flow stack with a bi-furcated (non-uniform) discharge nozzle, the velocity profile should be characterized by at least six velocity transverses across the top of the wind band (30 degrees apart), with six velocity measurements per travers, as shown in Figure 4. If possible, measurements should be obtained when the wind is blowing parallel to the gap between the two nozzles and when the wind is blowing perpendicular to the gap between the two nozzles.
Analysis and Reporting

Results from the Characterization Testing should be presented graphically with flow vectors showing the distribution of measured velocities across the top of the wind band for each of the five velocity ratios. The distributions should be characterized by the percentage of measured velocities that are within a factor of 3 of the maximum measured velocity (Figure 5). The total volume flow rate ($\Sigma V_n \cdot A_n$) and exit momentum ($\rho \Sigma V_n \cdot A_n$) should also be calculated for each of the five velocity ratios by applying an equally contributing area to each of the data points. The total volume flow rate should also be presented as a ratio of the volume flow rate out of the nozzle, commonly referred to by induced flow manufacturers as the dilution ration.

Fan Performance Testing

The performance of each plume should be evaluated by measuring the plume centerline, vertical spread, and lateral spread at 5 or more downwind distances from the fan. During each test, a tracer gas should be injected into the fan air supply duct at a known rate that is sufficient to be detected at the furthest most receptor location. The tracer gas concentration should not be of sufficient quantity and/or density to alter the combined density of the emitted gas (tracer gas plus ambient air) by more than 10%.
If a tracer gas is used that may be present in the ambient air at concentrations greater than 10% of the lowest measured concentration within the plume, background concentrations should be periodically measured upwind of the exhaust stack and the measured background values should be subtracted from all measured data within plume flow field.

Each fan should be evaluated at the same operating conditions identified above (i.e., exit velocity ratios ranging from 0.5 to 5.0). The testing should include a sufficient number of samples at each velocity ratio to provide a sample variance of no greater than 10% of the sample mean for the height of the plume centerline and no greater than 20% of the sample mean for the plume width and height.

Figures 6 and 7 below show a sample grid of potential measurement locations. All data can be obtained simultaneously. However, to get accurate results for the lateral spread of the plume, it may be advantageous to define the plume height for each measured configuration so that the lateral grid can be set at an appropriate elevation above the local grade. Sampling points along the grid should be position so that the maximum measured concentration at each downwind distance is no more than one grid point from the middle of the grid (i.e., with five sample points at each distance and orientation, there should be at least one sample point on either side of the location maximum of maximum concentration). It is anticipated that these sampling points are fixed in space, such as on towers, however, mobile sampling (such as from drones) is also acceptable, as long as the total sample time is sufficiently short such that the wind condition do not change during the test. Furthermore, validation must be provided to indicate that the presence of the tower or rotor wash from a drone, or other mounting device does not impact the validity of the samples.

**Analysis and Reporting**

Results from the Characterization Testing for the induced flow exhaust stacks should be compared with dispersion estimates using the methods outlined in Cimorelli et al. (2005) and in the Chapter 45 of the ASHRAE HVAC Applications (ASHRAE, 2017). In short, the horizontal, $\sigma_y$, and vertical, $\sigma_z$, dispersion coefficients are a function of downwind distance, $x$, and the surface roughness, $z_0$. Note that the site description for this study is designed to be similar to an open country to suburban environment with a surface roughness value between 10 cm and 30 cm. At each downwind distance and for each velocity ratio, the lateral and vertical spread of the plume should be fitted to a Gaussian distribution to calculate the standard deviation in the plume distribution in each direction ($\sigma_y$ and $\sigma_z$).
The vertical distribution should also be used to calculate the height of the centerline of the plume, $h_{plume}$, corresponding to the maximum measured concentration value in the vertical direction.

**Figure 7. Lateral and vertical plume distributions fitted to a Gaussian Distribution**

The resulting standard deviations values should be compared to predicted values using the equations outlined in Cimorelli et al. (2005) and in the ASHRAE HVAC Applications Handbook (ASHRAE, 2017) Chapter 45. To obtain these estimates, the appropriate measurements from the meteorological tower are required. An example comparison is shown in Figure 9.

**Figure 8. Pasquill-Gifford lateral, $\sigma_y$, and vertical dispersion coefficients, $\sigma_z$, as a function of downwind distance and atmospheric stability category**

The measured plume height, $h_{plume}$, should be compared against the Briggs’s plume rise equations, as described in the ASHRAE HVAC Applications Handbook (ASHRAE, 2017) Chapter 45. To normalize the results, the values should be plotted as a function of the velocity ratio, as shown below in Figure 10.

Statistical hypothesis testing should be conducted to determine if the measured plume performance for each entrained flow stack can be considered equivalent to, or different from, the plume performance from the conventional stack and the ASHRAE predicted values. If the measured values and predictions agree well, then the plume rise equations and entrainment relationship in Chapter 45 can be considered appropriate for the induced flow stacks. If not, further research to develop a method to evaluate the plume performance from induced flow fans should be suggested.
Figure 9. Brigg’s plume rise calculations vs. observed values; normalized by velocity ratio.

Deliverables:

1. Preliminary selection of induced flow and conventional fans for review and approval by PMS.
2. Preliminary layout of test site and instrumentation for review and approval by PMS.
3. Results of the first round of testing using the benchmark centrifugal fan to validate that the fan has the appropriate “top hat” fully developed turbulent profile at the stack exit and that the downwind plume profiles align with the published curves for plume rise and plume size.
4. Progress and Financial Reports must be sent to the PMS at quarterly internals during the contract period.
5. The Principal Investigator shall report to TC 9.10 during the summer and winter ASHRAE meetings.
6. At the completion of the data collection, the Principal Investigator shall prepare a preliminary report to be reviewed by the PMS to determine whether or not sufficient data has been obtained to adequately define the performance of each of the induced flow stacks.
7. The preliminary report should include:
   a. A full description of the test site, including dimensional drawings and aerial photographs showing the presence of any nearby structures and their distance from the site;
   b. A description of the instrumentation and applicable calibrations used throughout the project;
   c. A listing of the induced flow stacks used in the assessment, including AMCA certified fan curves;
   d. Data files of measured velocities across the top of the wind bands and the corresponding wind speed, wind direction, temperature, and barometric pressure;
   e. Vector plots of the velocity profiles above each wind band and a function of the velocity ratio;
   f. Calculations of the Vmax/3 value for each profile;
   g. Ratio of total volume flow rate out of the wind band to the total volume flow rate out of the nozzle (dilution ratio) for each velocity ratio;
   h. Data files of measured concentrations at each sampling location with the corresponding volume flow rate, inlet static pressure, wind speed, wind direction, ambient temperature, and barometric pressure.
   i. Plots of the lateral and vertical plume distributions at each downwind distance for each velocity ratio and fan selection;
   j. Calculated $\sigma_y$, $\sigma_z$, and $h_{plume}$ values at each downwind distance for each velocity ratio and fan selection;
   k. Plots comparing the observed lateral and vertical dispersion coefficients vs. the calculated values from Cimorelli (2005) at each downwind distance for each velocity ratio and fan selection;
   l. Plots comparing the observed plume rise vs. the Brigg’s plume rise equations at each downwind distance and fan selection, normalized by velocity ratio;
   m. General conclusions regarding the validity of the data, hypothesis testing on whether or not there is a significant difference in the performance between any of the induced flow stacks, the benchmark conventional fan, and the theoretical performance; and
n. Guidance on future research.

8. After the review and acceptance of the preliminary report by the PMS, the Principal Investigator shall prepare and submit a final report to the PMS addressing all comments received from the PMS.

9. The Principal Investigator should also produce at least one research paper to be submitted to the ASHRAE Manager of Research and Technical Services (MORTS).

10. The Principal Investigator should provide input into future updates of the ASHRAE Handbooks and Design Guides, as applicable to the findings of the research. This should include, but not be limited to ASHRAE Handbook – HVAC Applications Chapter 45 Building Air Intake and Exhaust Designs; ASHRAE Handbook – HVAC Systems and Equipment Chapter 21 Fans; ASHRAE Handbook – Fundamentals, Chapter 24 Air Flow Around Buildings; and the ASHRAE Laboratory Design Guide.

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.

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 Science & Technology for the Built Environment or 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 (1835-RP) at the end of the title in parentheses, e.g., (1835-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 documenting: (i) the main findings of the research project, (ii) why the findings are significant, and (iii) how the findings benefit ASHRAE membership and/or society in general.

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**

The level of effort is expected to include approximately 100 hours for site design; 180 hours for site installation; 600 hours for data collection; and 80 hours for analysis and preliminary reporting; and 80 hours for final reporting and technical paper preparation. Site design should take up to 2 months; site installation 6 months; data acquisition and analysis up to 12 to 18 months; and reporting 2 months. Total project time should be 24 to 30 months. Budget: $245,000

**Proposal Evaluation Criteria**

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<tr>
<th>No.</th>
<th>Proposal Review Criterion</th>
<th>Weighting Factor</th>
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<tbody>
<tr>
<td>1</td>
<td>Display a clear understanding of the project goals and knowledge of the atmospheric boundary layer physics.</td>
<td>10%</td>
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<td>2</td>
<td>Clear and concise project work plan with well-defined tasks and key milestones as well as a reasonable project schedule.</td>
<td>10%</td>
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<td>3</td>
<td>Experience conducting field concentration and velocity measurements</td>
<td>10%</td>
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<td>4</td>
<td>Access to an applicable test site with adequate clear space, minimal terrain, power requirements, and a favorable wind frequency distribution.</td>
<td>30%</td>
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<td>5</td>
<td>Demonstration of sufficient personnel resources to complete the project in a timely manner</td>
<td>20%</td>
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<tr>
<td>6</td>
<td>Experience with previous ASHRAE sponsored research, from either serving on a PMS or as a Principal Investigator.</td>
<td>10%</td>
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<tr>
<td>7</td>
<td>Suggestions for improving the effectiveness of the research or reducing project costs or schedule.</td>
<td>10%</td>
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### Project Milestones:

<table>
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<tr>
<th>No.</th>
<th>Major Project Completion Milestone</th>
<th>Deadline Month</th>
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<tbody>
<tr>
<td>1</td>
<td>Design of test site and development of a method of procedure for data collection and analysis.</td>
<td>4</td>
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<tr>
<td>2</td>
<td>Site installation of instrumentation, test bench, and exhaust fans</td>
<td>8</td>
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<tr>
<td>3</td>
<td>Data collection of velocity profiles across top of wind bands and downwind concentration profiles</td>
<td>12</td>
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<td>for 1st fan (i.e., the benchmark centrifugal fan). Submit results to PMS for verification of proper data collection and analysis techniques.</td>
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<tr>
<td>4</td>
<td>Data collection of velocity profiles across top of wind bands and downwind concentration profiles</td>
<td>20</td>
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<td></td>
<td>for 5 fans</td>
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<tr>
<td>5</td>
<td>Analysis of results and submission of Preliminary Report</td>
<td>24</td>
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<tr>
<td>6</td>
<td>Submission of Final Report and Research Paper</td>
<td>30</td>
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### References

**Additional Information**

In selecting the instrumentation for collecting downwind concentrations from the exhaust fans, it is paramount that all samples within the grid are collected for a sufficient duration to obtain steady-state average concentration values. If all samples are not collected simultaneously, then the wind speed and wind direction deviation during the entire sample time should be evaluated to determine whether or not valid data was collected. Recommended sample durations and the number of samplers employed has not been specified, but rather it has been left up to the investigator to properly define. Proper sampling technique is critical to obtaining accurate and repeatable results. Furthermore, the tracer concentration and gas type to be used during the plume performance tests has not been specified. But it is assumed that the researcher will adhere to all federal and local regulations associated with health, safety and GHG emission standards.

Greenheck, M.K. Plastic, and Loren Cook have agreed to provide one or more induced flow stacks for this research project. However, it is the responsibility of the researcher to coordinate with these (and other) fan manufacturers on the selection and delivery of the fans to the site and to make sure that each of the fans are installed and operated per the manufacturer’s instructions.

**Glossary of Terms:**

Conventional Stack – A straight vertical stack with a constant cross-section (typically round) that extends at least 5 diameters above the exhaust fan. A conventional stack will have a fully developed turbulent velocity profile at the top of the stack prior to being vented to the atmosphere if it has a stack height to width ratio (H/D) >>1 and an internal Reynolds Number of at least 2300 to 4000 (Snyder, 1981). The exact H/D to achieve fully developed flow depends upon the internal flow Reynolds Number and the relative roughness of the internal surface of the stack. An H/D value of 10 is often considered sufficient for most applications, with only minor deviations in the velocity profile occurring between H/D values of 5 to 10.

Fan Nozzle – The orifice at the top of the fan where the air flow passing through the fan exits. For an induced flow stack, the nozzle is typically located concentric to and near the bottom of the wind band. The fan nozzle might be a single orifice or multiple orifices, such as with a bi-furcated nozzle, which is common for certain induced fan manufacturers.

Fully Developed Flow – Flow in a stack becomes fully developed when the general shape of the velocity profile across a horizontal plane of the stack is unchanging as the flow continues up the stack. In laminar flow, the velocity profile of a fully developed flow tends to be parabolic shaped, or at its maximum only near the centerline of the stack. Near the edge of the stack the velocities drop off due to frictional losses along the side of the stack. In turbulent flow, the lateral profile across the stack is more constant and often described as being a “top hat” distribution where the velocity across most of the profile is similar in magnitude and only drops off near the edge of the stack.

Induced Flow Stack - An exhaust fan which is equipped with a high velocity nozzle that is enclosed within an external structure (wind band) that is designed to induce air from the ambient area surrounding the fan and mix with the air exiting the top of the nozzle.

Irregular Velocity Profile – The velocity profile across a horizontal plane of the stack is not symmetric about the centerline of the stack in one or more directions. Velocity profiles become irregular due to insufficient length between the inlet and outlet conditions, or when an outside force is not equally apply across the entire flow field. For the stacks included in this assessment an irregular flow can be caused by the merging of two flow fields, such as with bi-furcated nozzles or between the flow out the top of the fan nozzle and the induced flow entering from below the wind band.

Laminar Flow – A fluid flow where the fluid moves in parallel stream lines with little or no mixing between the stream lines (the opposite of turbulent flow). In laminar flow there are no swirls or eddies that might create mixing between stream lines. Laminar flow only occurs at very low velocities or in highly viscous fluid. Laminar flow is unlikely to occur within the exhaust stacks that are the subject of this investigation.

Plume Performance – The trajectory and size of the exhaust plume emanating from the top of the stack as it travels downwind. This is characterized by the plume rise and the lateral and vertical spread of the plume as a function of...
the downwind distance from the stack for a specified wind speed and/or velocity ratio (stack exit velocity/wind speed at the top of the stack).

Transitioning Velocity Profile – The shape of the velocity profile in one or more horizontal planes across the stack is changing as the fluid moves up the stack (the opposite of a fully developed flow profile). Pipe flow theory for smooth surfaces indicates that it takes between 5 and 10 diameters after a disruption in the flow before it becomes fully developed. Disruptions can include the merging of two or more flows and/or changes in direction of the flow.

Turbulent Flow – A fluid flow where the movement of the flow includes irregular fluctuations in both the direction and magnitude, resulting internal mixing of the fluid flow (the opposite of laminar flow). The flow of air through all of the exhaust stacks that are subject of this investigation are expected to be turbulent within and external to the nozzle.

Wind Band – A physical structure, typically in the shape of a cone, that encircles the nozzle at the top of the fan. The structure is open at the bottom to allow ambient air flow to enter and be induced into the higher velocity air flow exiting the top of fan nozzle. The wind band is also open at the top to allow the combined fan and induced air flows to be exhausted to the atmosphere.