

## INVITATION TO SUBMIT A RESEARCH PROPOSAL ON AN ASHRAE RESEARCH PROJECT

### 1769-TRP, “Experimental Evaluation of the Efficiency of Belt Drives for Fans”

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: TC 5.1, Fans  
Co-sponsored by: N/A

Budget Range: \$120,000 may be more or less as determined by value of proposal and competing proposals.

Scheduled Project Start Date: **September 1, 2018** or later.

**All proposals must be received at ASHRAE Headquarters by 8:00 AM, EDT, May 15, 2018. NO EXCEPTIONS, NO EXTENSIONS.** Electronic copies must be sent to [rpbids@ashrae.org](mailto:rpbids@ashrae.org). Electronic signatures must be scanned and added to the file before submitting. The submission title line should read: 1769-TRP, “Experimental Evaluation of the Efficiency of Belt Drives for Fans” 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

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#### For Administrative or Procedural Matters:

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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 1, 2018 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](mailto:rpbids@ashrae.org).**

**All other correspondence must be sent to [ddaniel@ashrae.org](mailto:ddaniel@ashrae.org) and [mvaughn@ashrae.org](mailto:mvaughn@ashrae.org). In all cases, the proposal must be submitted to ASHRAE by 8:00 AM, EDT, May 15, 2018. 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 reserves the right to reject any or all bids.**

### **State of the Art (Background)**

Belt drives have long been used to match fixed-pole motor speeds with fan speeds required to achieve operating airflows and pressure rises. With low investment cost, they provide torque and speed conversion that is adjustable in field installations. Although there is an increasing trend toward direct drive fans in many applications, it is recognized that the need for high efficiency belt drives remains especially for low speed fans that operate at high torque. For fans sold with 1 hp through 300 hp motors, a major commercial fan manufacturer (Greenheck Fan) reports that over 80% of these sales are belt driven.

Notched or synchronous belt drives are an alternative to conventional wrapped V-belt drives and provide better efficiency [DOE 2012, Gates 2014]. However, their disadvantages have outweighed their efficiency advantage resulting in the continued prominence of conventional V-belt drives.

Belt drive efficiency is generally defined as the power input to the fan pulley divided by the power output by the motor pulley. More specifically, because mechanical power in this case is the product of speed and torque, efficiency can be defined as [De Almeida and Greenberg 1995]:

$$\eta_{belt} = 100 \left( \frac{\omega_{fan} T_{fan}}{\omega_{motor} T_{motor}} \right) \quad (\text{Equation 1})$$

where

- $\eta_{belt}$  = Belt drive efficiency, %
- $\omega_{fan}$  = Fan shaft rotational speed, rpm
- $T_{fan}$  = Net torque on fan shaft pulley, in-lb<sub>f</sub>
- $\omega_{motor}$  = Motor shaft rotational speed, rpm
- $T_{motor}$  = Net torque on motor shaft pulley, in-lb<sub>f</sub>

The net torque for each pulley is defined as the net belt pull (tangential force acting on the tight side of the belt minus the tangential force acting on the slack side) multiplied by the pulley pitch radius [Euler 1769, Lubarda 2015]. These forces are also speed dependent due to the rapidly increasing effects of centrifugal force on the belt as pulley speeds increase (centrifugal force varies with the shaft speed squared). Centrifugal forces also reduce the belt angle of contact for each pulley as the pulley speeds increase, which in turn can lead to increased slip [Faires 1965].

Belt drives have inherent bending and frictional losses at each pulley, which affect the drive forces and thus the net torque at the pulleys. Bending (hysteresis) losses are load (torque) *independent* while frictional losses are load *dependent*. Belts are also subject to slip- and creep-related speed losses. The latter occurs because the belt elongates differently at each pulley's entry and exit, which in turn causes the belt to "creep" around the pulleys and thus reduce the fan shaft speed. There are many design and operation variables that affect these losses and thus belt drive efficiency. They include: belt type and cross-section, pulley diameters, shaft to shaft distance, power delivered, and service (oversizing) factor [Kong 2003, Carlisle 1980].

As a result, belt drive efficiency depends on the specific design and operating point of the belt drive system. It also varies with belt loading and speed in variable-speed fan applications, when they operate at power levels significantly lower than the drives are designed to carry. Accurate and reliable information on fan belt drive efficiency at full-load (design) and part-load conditions is not generally available and the impact of the many variables that affect part-load efficiency is also not currently well known. It is also difficult to use fundamental engineering principles related to belt static and dynamic loading to analytically determine belt drive efficiency. However, even though performance data for V-belt drives do not normally reference full vs. part load or operating conditions, they do provide maximum rated loads and service factors that can be used to indicate the actual loading in relation to this maximum rated load.

For example, AMCA 203 provides a rough estimate of V-belt drive losses at design capacity, but this estimate varies only with motor power and is based on a small number of tests conducted many years ago [AMCA 1990]. ISO 12759 has an entirely different estimate of drive efficiency that is more of a straight line approximation based on

power [ISO 2010]. Recent controlled experiments have shown a strong correlation between transmission efficiency and output torque [Dereyne et al. 2013]. An unpublished experiment conducted at Lawrence Berkeley National Laboratory (LBNL) in 2013 is attached as Appendix A to illustrate that this effect is highly non-linear and that belt efficiency decreases substantially with speed and load. Appendix B illustrates how this behavior can affect system efficiency.

### **Objective**

- Perform a review of available literature, articles, and previous testing of belt drive efficiency, including any existing formulas or algorithms for calculation of belt drive efficiency.
- Develop a method of test and test equipment characteristics that will ensure accurate test results over a belt drive power range of 1 to 100 hp.
- Determine experimental variables and outline a test program that will enable the impact of key variables on belt drive efficiency to be quantified at full and part-load.
- Conduct efficiency testing on fan belt drives covering the range of variables identified.
- Analyze results to establish the dependence of belt drive efficiency on the variables identified.

Develop algorithms to predict full-load efficiency for belt drives along with the expected variation of efficiencies at part-load.

### **Scope:**

This project involves lab testing, as well as data analyses and modeling.

Bidders on this work statement are expected to demonstrate expertise with measuring mechanical drive system efficiency, as well as shaft power, speed, and torque. Bidders should have a thorough understanding of fan system and belt drive design and applications.

### **Task 1: Identify, Review, and Analyze Existing Data Sources**

A literature search of recent research on drive belt efficiency testing and modeling will be carried out by the bidder and all pertinent references will be summarized. This review will include interviews with belt drive suppliers and fan manufacturers to determine typical drive selection tools and procedures. The search shall include research carried out in other industry sectors that might be applicable (e.g., the automotive and industrial sectors).

*Task 1 Deliverable:* Interim Report 1 containing a summary of all pertinent prior work from the literature. Documents referred to shall be listed in the form of an annotated bibliography that follows the summary. Unless otherwise specified, the report shall be furnished electronically for review by the PMS. The Contractor shall not proceed with the next tasks until Task 1 deliverables are approved by the PMS.

### **Task 2: Method of Test**

The test rig and equipment used must be selected to ensure accurate results covering the entire scope. Some of the variables tested in this project could have an impact on the accuracy of measurement. For example, some sensors used for measuring torque may be sensitive to radial or axial forces. Because some of the variables studied in this project will influence radial or axial forces, the torque sensing accuracy must be independent of these forces. For data acquisition and data reduction purposes, the location and types of transducers for measuring shaft speed and torque, as well the instruments used to assess belt drive tension and alignment, shall be proposed by the bidder for review and approval by the Project Monitoring Subcommittee (PMS).

A preliminary list of test variables (e.g., transmitted power, speed ratio, number of belts) shall be developed by the bidder based on the literature search for review and approval by the PMS. Sensitivity to each of these variables shall be evaluated by the bidder. Variables that appear to be significant shall be tested in more detail by the bidder and those determined to be insignificant will not be studied. In this way, preliminary sensitivity testing will dictate subsequent test planning. A test plan based on the selected variables shall be developed by the bidder for review and approval by the PMS.

*Task 2 Deliverable:* Interim Report 1 containing a description of the test equipment, preliminary and final test variable list, and test plan. Unless otherwise specified, the report shall be furnished electronically for review by the PMS. The Contractor shall not proceed with the next tasks until Task 2 deliverables are approved by the PMS.

### **Task 3: Testing**

For this project, new experimental data will need to be collected to supplement data that might be available in the literature. This task involves performance testing of belt drives for fans that covers a range of belt types (wrapped and notched), belt cross sections (A, AX, B, BX, 5VX), speeds, torques, drive ratios, and service factors that are commonly used in HVAC fan systems. Depending on the test variables selected in Task 2, the testing will likely cover 20 to 40 different belt and pulley combinations, all correctly aligned and tensioned according to belt manufacturer specifications.

A segment of the tests shall also be conducted at reduced speeds and torques to represent the variable loading of a fan in a typical variable-air-volume system and the reduction in belt drive efficiency at part load.

Additionally, the effect of belt tensioners (e.g., the Fenner Drives “T-Max” Tensioner) shall be tested, because they introduce additional bending and frictional losses that reduce drive efficiency.

Sufficient repetition of the test process shall be documented to satisfy the PMS that the test results are repeatable. The bidder shall propose a repeatability threshold and provide associated reasoning to support its selection so that the threshold can be used for test result review and approval by the PMS. All analyses shall include uncertainty estimates, which shall be conducted according to the rules described in the “Guide to the expression of uncertainty in measurement” [JCGM 2008].

*Task 3 Deliverables:* Interim Report 2 describing the test data and calculated efficiency results for each drive combination tested. Details shall include:

- a) The characteristics of the drive combinations tested (including belt types, belt cross sections, number of belts, pulley diameters, drive ratios, service factors, and pulley speeds and torques).
- b) The effects of full and part-load operation on the power transmitted and belt drive efficiency.
- c) The effects of belt tensioners on the power transmitted and belt drive efficiency.

The report shall include uncertainty estimates for each measured and calculated parameter and their method of calculation. The repeatability of test results and the proposed threshold criteria shall also be reported, along with the associated reasoning to support its selection. Unless otherwise specified, the report shall be furnished electronically for review by the PMS. The Contractor shall not proceed with the next task until Task 3 deliverables are approved by the PMS.

### **Task 4: Develop and Verify Model**

The test results will be used to develop two different models for belt drive efficiency. The first model shall provide an estimation of the efficiency for a specific drive configuration. Depending on which variables are identified as being most important, this specific configuration will include a number of variables such as the power transmitted, speed ratio, belt cross section, pulley diameters, and number of belts. This model is intended to be used as an aid in selecting and evaluating a specific drive combination for an application.

The second model shall estimate efficiencies for typical V-belt drives, independent of the specific drive configuration. AMCA 203 provides an example of such a model (as a possible starting point), because it uses a simple relationship between drive efficiency and power consumed. This general model shall be based on as few variables as possible while still providing reasonable accuracy. This model is intended to be used to estimate transmission efficiency for standards, codes, and regulations.

*Task 4 Deliverables:* Final report containing: a) The specific configuration model in the form of tables or charts covering the range of components tested. b) The general model as a mathematical function of the variables chosen. c) Expected deviations of the models relative to the measured data shall also be provided. The two interim reports describing the outcomes of Tasks 1 through 3 shall be included as report chapters.

The final report shall be in a form approved by the Society and shall be submitted to the Society’s Manager of Research and Technical Services (MORTS) by the end of the Agreement term, containing complete details of all research carried out under this Agreement, including a summary of the project findings. Unless otherwise specified,

the *draft* final report shall be furnished electronically for review first by the PMS. The Contractor shall not finalize the report until the draft is approved by the PMS.

Tabulated values for all measurements shall be provided as an appendix to the draft final report (for measurements that 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 sponsoring TC/TG, in their sole discretion, final copies of the final report will be provided by the Contractor 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.

**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.

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 (1769-RP) at the end of the title in parentheses, e.g., (1769-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**

It is expected that this project will take 18 months to complete at a total cost of \$120,000, with at least 15% of the time (2.7 months) attributed to the Principal Investigator.

The funding listed is for labor and indirect costs. It is expected that the bidder will already have suitable test equipment to carry out the research, so the proposed budget does not include this cost. Also, it is anticipated that the bidder will arrange for pulleys and belts used for testing to be donated by manufacturers (i.e., as possible co-funding), and the proposed budget does not include this cost.

**Proposal Evaluation Criteria**

No.	Proposal Review Criterion	Weighting Factor
1	Contractor's understanding of the Work Statements as revealed in the proposal.	20%
2	Quality of testing facility and methodology proposed for conducting research: a. Proposed test facility b. Proposed methodology. c. Data collection and analysis techniques.	30%
3	Qualification of personnel for this project: a. Experience with mechanical drive system testing. b. Experience with fan system design and belt drive mechanics. c. Time commitment of principal investigator. d. Other team members' qualifications.	30%
4	Organization: a. Detailed work plan with major tasks and key milestones. b. All technical and logistic factors considered. c. Reasonableness of project schedule.	15%
5	Performance of contractor on prior ASHRAE projects (no penalty for new contractors).	5%

**Project Milestones:**

No.	Major Project Completion Milestone	Months from Project Start
1	Interim Report 1 documenting literature review, test equipment, test variables, and test plan (Tasks 1 and 2)	6
2	Interim Report 2 documenting test results, uncertainty estimates, and calculation methods (Task 3)	12
3	Final Report documenting models and expected deviations from measured data (Task 4), along with complete details of all research carried out under the Agreement.	18

**References**

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3. ASHRAE. 2016. "Research Manual: SY 16-17 Edition". Revised May 5. Atlanta, GA: ASHRAE. [https://www.ashrae.org/File%20Library/docLib/Research/Research-Manual-A16-17\\_r1.doc](https://www.ashrae.org/File%20Library/docLib/Research/Research-Manual-A16-17_r1.doc).
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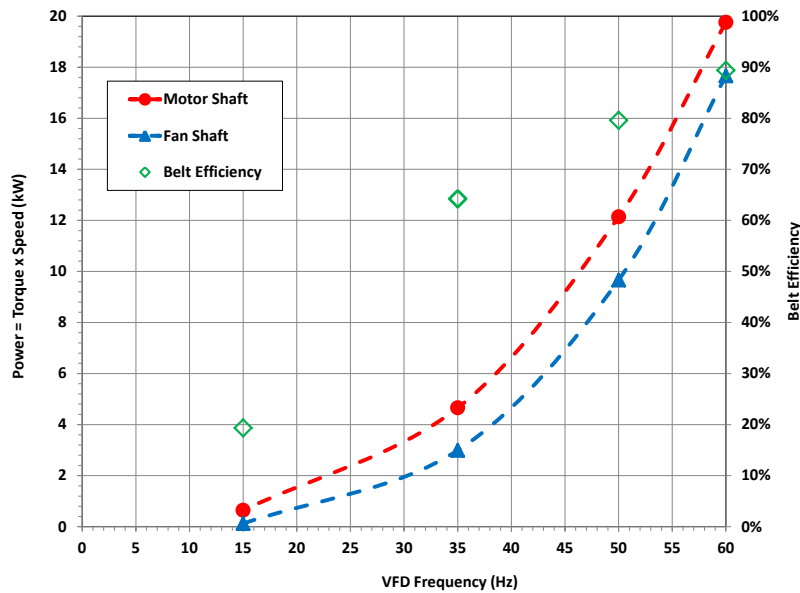
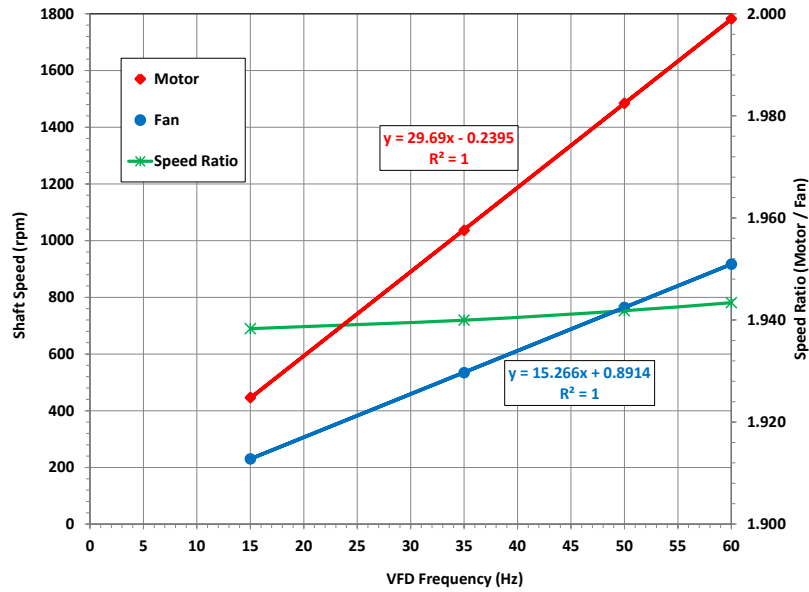
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**Appendix A: Preliminary V-Belt Drive Test Results [LBNL 2013, Unpublished]**

**Tested System:** Centrifugal DWDI backward-inclined fan (Aladdin Type BB Size 365) driven by 30 hp variable-speed electric motor (rated at 1770 rpm); shaft to shaft centerline span: 48.75 in.; pulleys are three-groove Browning Q-D types: 3B184SK (fan, 18.75 in. OD) and 3B94SK (motor, 9.75 in. OD), aligned (angular, parallel, and offset) using reflective laser optical system; each of three V-belts is Gates Hi-Power II B139 V80, initial tension set to manufacturer specifications using deflecting belt tension gauge and confirmed with sonic tension meter

**Measurement Equipment:** Fan shaft and motor shaft torque and speed measured using two Sensor Developments Inc. pulley torque and speed meters (custom-made, factory-calibrated); modified pulley hubs each include strain gauge; associated shaft-end-mounted stationary instrument package connected to strain gauge through slip rings and includes optical speed encoder; sensor outputs recorded using Fluke 289 digital logging multimeter.

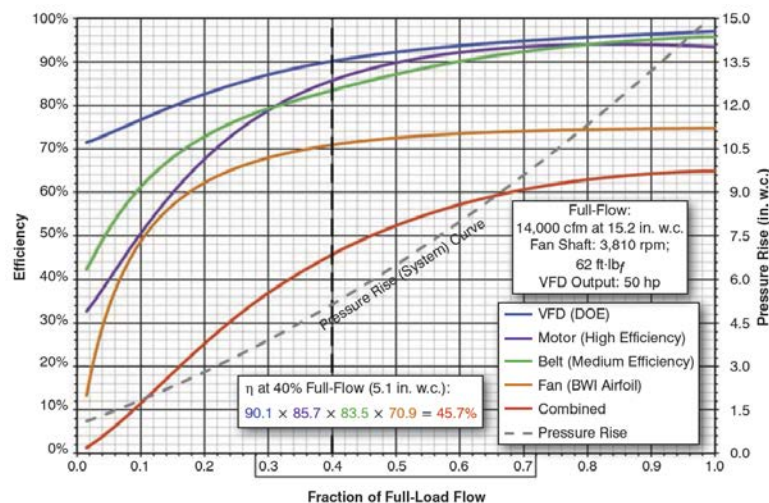


## Appendix B: Effects of Belt Drive Efficiency Variations on Fan System Efficiency

Fan systems used to move air for space conditioning and ventilation in buildings seldom operate at design load, simply because this condition rarely occurs by definition and also due in part to component oversizing practices. Many fan systems use more energy than necessary to, partly because the industry does not account for the impacts of fan component efficiency variations during part-load operation. In this regard, one of the components usually ignored is the belt drive. To illustrate how belt drive efficiency variations with load can significantly affect fan system efficiency and energy use, consider the fan system example described in Krukowski and Wray [2012].

As stated by Krukowski and Wray, over roughly the past 45 years, mainstream building simulation software, as well as related codes and standards, have assumed that fan system efficiency is based on fan and motor efficiencies *at design conditions* (belt and variable frequency drive efficiencies are not addressed separately), and that part-load variations of system efficiency can be described by polynomial curves that represent the various types of fan airflow control (e.g., discharge dampers, inlet vanes, and variable speed control). Commonly used energy analysis computer programs all use the same polynomial curves, which appear to be derived from NECAP [Henninger et al. 1975] and the early 1970s work of the ASHRAE Task Group on Energy Requirements for Heating and Cooling of Buildings [Stoecker 1975]. The source of the data used to generate the curves is unknown, but may be from unpublished tests in the late 1960s or early 1970s at one manufacturer’s laboratory [Hittle 2008]. However, these curves are not always appropriate because their default coefficients do not account for in component efficiency variations at part-load when the system components differ from the systems that were tested (for which the individual component characteristics are unknown). Generating system specific coefficients would require a priori knowledge of component and/or whole-system performance.

As a step toward correcting this deficiency, in 2010 Wray updated EnergyPlus, which is the U.S. Department of Energy’s (DOE) flagship building energy simulation computer program [DOE 2010]. EnergyPlus now contains a component-based fan system model, which explicitly describes the variations in component efficiency at part-load for each individual component. More specifically, the “component model” includes a “system curve” (fan pressure rise) model (including the effects of system air leakage and duct static pressure set points) [Sherman and Wray 2010], dimensionless fan efficiency and speed models, motor and variable frequency drive (VFD) models, and a *simple belt model based on very limited data*. These models are intended for time-dependent analyses (and integration of sub-hourly results to estimate annual performance), so that designers can more accurately predict building energy use and to help size components more appropriately. The following figure shows an example plot of efficiency variations generated using the EnergyPlus models for a hypothetical but realistic system.



The efficiency curves shown in this figure represent a commercially available 18 in. (0.46 m) diameter double-width double-inlet backward-inclined airfoil centrifugal supply fan with a 14,000 cfm (6.7 m<sup>3</sup>/s) design flow at 15.2 in. w.c. (3,780 Pa), which corresponds to a speed of 3,810 rpm at a torque of 62 ft·lbf (84 N m); a “medium efficiency” V-belt; a “high efficiency” motor; a variable-frequency drive (VFD) with a 50 hp (37 kW) rated output; and a variable air volume (VAV) supply air distribution system with coil and filter elements and a duct static pressure set point of 1 in. w.c. (249 Pa). In SI units, the “system curve” used here has the form:

$$\Delta p = 42.2 Q^2 + 295 Q + 249$$

where  $\Delta p$  is the fan pressure rise (Pa) and  $Q$  is the fan airflow ( $\text{m}^3/\text{s}$ ).

The efficiencies for the VFD, motor, belt, and fan, respectively, at full flow are about 97%, 94%, 96%, and 75%. The fan *system* efficiency at full flow is thus  $0.97 \times 0.94 \times 0.96 \times 0.75 = \mathbf{66\%}$ .

Part-load efficiencies, speeds, and flows for the fan were derived from the manufacturer's performance map (using dimensionless relationships described in the EnergyPlus fan component model) and the system curve. At each operating point along the "system curve", part-load efficiencies for the belts, motor, and VFD, respectively, were derived from full-load efficiency data for V-belts provided by AMCA [1990] and part-load characteristics provided by Nadel et al. [2002], from DOE MotorMaster+ data [Washington State University 2010], and from the "DOE" 50 hp (37 kW) VFD efficiency curve described by Krukowski and Wray [2012].

For the example system, at 40% of full flow (near where the system curve crosses the fan's "do not select" curve), the part-load efficiencies for the VFD, motor, belt, and fan are lower than at full load: about 90.1%, 85.7%, 83.5%, and 70.9%, respectively. The part-load fan *system* efficiency is thus much lower here than at full load: about **46%** (or about a *20 point decrease* from full load).

If the drive belt efficiency was *incorrectly* assumed to be constant (same value as at full-load: 96%), the part-load *system* efficiency would instead be **53%** (7 points higher than it is with the belt part-load efficiency correctly stated). In terms of energy use at part load, properly including the difference of 7 points in system efficiency means that the system in this example would actually use  $0.53/0.46 = \mathbf{15\% \text{ more energy}}$  at 40% part load than if the variation in belt efficiency was ignored. This difference can be especially significant for VAV systems that often operate at these low part load ratios over the year (e.g., an office building located in Chicago).

#### **Additional References for Appendix B**

1. ASHRAE. 2012. "ASHRAE Handbook - HVAC Systems and Equipment". Chapter 19, p.19.2.
2. DOE. 2008. "Motor Tip Sheet #11: Adjustable Speed Drive Part-Load Efficiency." U.S. Department of Energy Industrial Technologies Program.  
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3. Henninger, R.H. (ed). 1975. "NECAP—NASA's Energy-Cost Analysis Program, Part II – Engineering Manual." National Aeronautics and Space Administration Contractor Report prepared by General American Transportation Corporation, Nites, Ill. September. NASA CR-2590 Part II.
4. Hittle, Doug (University of Colorado). 2008. Personal communication with Craig Wray.
5. Krukowski, A. and C.P. Wray. 2012. "Standardizing Data for VFD Efficiency". ASHRAE Journal. June.  
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8. Washington State University. 2010. MotorMaster+ Version 4.01.01. Developed for the U.S. Department of Energy by the Washington State University Cooperative Extension Energy Program. September 21.



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TO: Franco Cincotti, Chair TC 5.1, [FCINCOTTI@comefriusa.com](mailto:FCINCOTTI@comefriusa.com)

FROM: Michael R. Vaughn  
Manager of Research and Technical Services

CC: Dennis Loveday, Research Liaison 5.0, [d.l.loveday@lboro.ac.uk](mailto:d.l.loveday@lboro.ac.uk)  
Brian Reynolds, Research Subcommittee Chair TC 5.1, [breyolds@trane.com](mailto:breyolds@trane.com)  
Timothy Mathson, Craig Wray, Work Statement Author(s), [tim.mathson@greenheck.com](mailto:tim.mathson@greenheck.com);  
[pharmeng@pacbell.net](mailto:pharmeng@pacbell.net)

DATE: October 11, 2017

SUBJECT: Work Statement (1769-WS), "Experimental Evaluation of the Efficiency of Belt Drives for Fans"

During their recent fall meeting, the Research Administration Committee (RAC) reviewed the subject Work Statement (WS) and voted 11-0-1 CNV to conditionally accept it for bid provided that the RAC approval conditions are addressed to the satisfaction of your Research Liaison in either written responses or revisions to the work statement.

1. Work statement authors did not provide specific response to RAC comments from RTAR.
2. Description of task deliverables for test data and calculated efficiency could use more description.
3. Co-funding framework need to be in on-board early on in the project development. Revise the co-funding framework.

See the bottom of the attached WS review summary for the approval conditions.

The WS review summary also contains comments from individual members of RAC that the TC may or may not choose to also consider when revising the WS; some of these comments may indicate areas of the WS where readers require additional information or rewording for clarification.

If PES roster changes are required, please review them with your RL, Dennis Loveday, [d.l.loveday@lboro.ac.uk](mailto:d.l.loveday@lboro.ac.uk), for approval.

Lastly, please provide ASHRAE staff with the final names and contact information for the Proposal Evaluation Subcommittee (PES) roster, and the Technical Contact that will respond to questions from prospective bidders during the bid posting period (typically this is a WS author or PES member). The technical contact and all members of the PES must also agree to not bid on this project.

Please coordinate changes to this Work Statement with your Research Liaison, [d.l.loveday@lboro.ac.uk](mailto:d.l.loveday@lboro.ac.uk), or [RL5@ashrae.net](mailto:RL5@ashrae.net). Once he is satisfied that the approval conditions have been met, the project will be ready to bid.

The first opportunity that you will have for this project to possibly bid is winter 2018. To be eligible for this bid cycle, a revised work statement that has been approved for bid by your research liaison should be sent (electronically) to Mike Vaughn, Manager of Research and Technical Services, [mvaughn@ashrae.org](mailto:mvaughn@ashrae.org) or [morts@ashrae.net](mailto:morts@ashrae.net), before December 15, 2017. The next opportunity for bid after that will be spring 2018.

<b>Project ID</b>	<b>1769</b>	
<b>Project Title</b>	Experimental Evaluation of the Efficiency of Belt Drives for Fans	
<b>Sponsoring TC</b>	TC 5.1, Fans	
<b>Cost / Duration</b>	\$120,000 / 18 Months	
<b>Submission History</b>	1st WS Submission, RTAR accepted A16	
<b>Classification: Research or Technology Transfer</b>	Basic/Applied Research	
<b>RAC 2017 Fall Meeting Review</b>	<b>RTAR STAGE FOLLOWED</b>	
<b>Check List Criteria</b>	<b>Voted NO</b>	<b>Comments &amp; Suggestions</b>
<b>State-of-the-Art (Background):</b> The WS should include some level of literature review that documents the importance/magnitude of a problem. If not, then the WS should be returned for revision. <b>RTAR Review Criterion</b>		
<b>Advancement to the State-of-the-Art:</b> Is there enough justification for the need of the proposed research. Will this research significantly contribute to the advancement of the State-of-the-Art. <b>RTAR Review Criterion</b>		
<b>Relevance and Benefits to ASHRAE:</b> Evaluate whether relevance and benefits are clearly explained in terms of: a. Leading to innovations in the field of HVAC & Refrigeration b. Valuable addition to the missing information which will lead to new design guidelines and valuable modifications to handbooks and standards.		
<b>IF THE THREE CRITERIA ABOVE ARE NOT ALL SATISFIED - MARK "REJECT" BELOW BUT ADDRESS THE FOLLOWING CRITERIA AS APPROPRIATE</b>		
<b>Detailed Bidders List Provided?</b> The contact information in the bidder list should be complete so that each potential bidder can be contacted without difficulty.		#12 - 6 potential bidders are identified.
<b>Proposed Project Description Correct?</b> Are there technical errors and/or technical omissions that the WS has that prevents it from correctly describing the project? If there are, than the WS needs major revision.		
<b>Task Breakdown Reasonable?</b> Is the project divided into tasks that make technical and practical sense? Are the results of each task such that the results of the former naturally flow into the latter? If not, then major revisions are needed to the WS that would include: adding tasks, removing tasks, and re-structuring tasks among others.		#12 - 4 Tasks are described with deliverables for each. #8 - Description of task deliverables for test data and calculated efficiency could use more description
<b>Adequate Intermediate Deliverables?</b> The project should include the review of intermediate results by the PMS at logical milestone points during the project. Before project work continues, the PMS must approve the intermediate results.		#11 - report 1 used for both tasks 1 and 2; I would prefer to have 1 interim report for each task. #8 - Ensure Task 4 work is identified not to start until task 3 is complete. I would prefer to see more milestones between No 1 & No. 2 at 6 and 12 months.
<b>Proposed Project Doable?</b> Can the project as described in the WS be accomplished? If difficulties exist in the project's WS that prevent a successful conclusion of the project, then the project is not doable. In this situation, major revision of the WS is needed to resolve the issues that cause the difficulty.		
<b>Time and Cost Estimate Reasonable?</b> The time duration and total cost of the project should be reasonable so that the project can be as it is described in the WS.		#12 - Three potential co-funding organizations are listed. Need commitments from them. I am surprised that after centuries of using belts and their prevalence in various applications, including automotive applications, that a study of this nature is needed. The authors of the WS do not even provide an estimate of the % power losses in built drive. Are these losses a significant fraction of the overall wire to air efficiency? #8 - Cost seems low for 18 months?
<b>Proposed Project Biddable?</b> Examining the WS as a whole, is the project described in the WS of sufficient clarity and detail such a potential bidder can actually understand and develop a proposal for the project? This criterion combines the previous three criteria into an overall question concerning the usefulness of the WS. If the WS is considered to not be biddable, then either major revisions are in order or the WS should be rejected.		#11 - although, their requirements for co-funding to be the responsibility of the bidder is a bit odd since that might create some unfavorable comparisons. CW - Requires more definition regarding number of tests required. Deliverables sections is fairly boilerplate. Should better describe format of deliverables such as the models. Are these models going to be computer programs? What type of software.
<b>Decision Options</b>	<b>Initial Decision</b>	<b>Final Approval Conditions</b>
ACCEPT		#11 - revise the co-funding framework. #12 - I am not convinced that the issue of built drive efficiency for fans or other equipment is still an unexplored area that requires \$120K of research and 18 months or work. I am willing to reconsider if: 1) the relative impact of the belt drive is quantified in the SoA, and 2) evidence is presented that work of this nature has not been done or is inaccessible to the HVAC industry. #8 - address task milestones above. #13 - WS authors did not provide specific response to RAC comments from RTAR. #3 - Good WS, through background information and there is an obvious need. Looks like RAC comments were addressed, however, TC did not provide a letter telling how RTAR comments were addressed in WS. ADDITIONAL CONDITION: Co-funding framework need to be in on-board early on in the project development.
COND. ACCEPT	X	
RETURN		
REJECT		

**ACCEPT Vote** - Work statement(WS) ready to bid as-is

**CONDITIONAL ACCEPT Vote** - Minor Revision Required - RL can approve WS for bid without going back to RAC once TC satisfies RAC's approval condition(s) to his/her satisfaction

**RETURN Vote** - WS requires major revision before it can bid

**REJECT Vote** - Topic is no longer considered acceptable for the ASHRAE Research Program due to duplication of work by another project or because the work statement has a fatal flaw(s) that makes it unbiddable

**WORK STATEMENT COVER SHEET**

Date: **27 April 2017**

(Please Check to Insure the Following Information is in the Work Statement )

- A. Title
- B. Executive Summary
- C. Applicability to ASHRAE Research Strategic Plan
- D. Application of the Results
- E. State-of-the-Art (background)
- F. Advancement to State-of-the-Art
- G. Justification and Value to ASHRAE
- H. Objective
- I. Scope
- J. Deliverables/Where Results will be Published
- K. Level of Effort
 

Project Duration in Months	<input checked="" type="checkbox"/>
Professional-Months: Principal Investigator	<input checked="" type="checkbox"/>
Professional-Months: Total	<input checked="" type="checkbox"/>
Estimated \$ Value	<input checked="" type="checkbox"/>
- L. Proposal Evaluation Criteria & Weighting Factors
- M. References
- N. Other Information to (Optional)

Title:  
**Experimental Evaluation of the Efficiency of Belt Drives for Fans**

WS# **1769**  
(To be assigned by MORTS - Same as RTAR #)

Results of this Project will affect the following Handbook Chapters, Special Publications, etc.:  
**Systems & Equipment S21, S45**

Responsible TC/TG: **5.1 "Fans"**

Date of Vote: **June 26, 2017**

For		<b>11</b>
Against	*	<b>0</b>
Abstaining	*	<b>0</b>
Absent or not returning Ballot	*	<b>2</b>
Total Voting Members		<b>13</b>

This W/S has been coordinated with TC/TG/SSPC (give vote and date):  
**N/A**

Has RTAR been submitted?  
Strategic Plan  
Theme/Goals  
**Yes**

Work Statement Authors: \*\*  
**Tim Mathson (Greenheck Fan)**  
**Craig Wray (Retired)**

Proposal Evaluation Subcommittee:  
Chair: **Tim Mathson**  
Members: **Brian Reynolds**  
**Craig Wray**

Project Monitoring Subcommittee:  
(If different from Proposal Evaluation Subcommittee)

Recommended Bidders (name, address, e-mail, tel. number): \*\*  
**Ghent University (Belgium), Dr. Kurt Stockman, Kurt.Stockman@UGent.be**  
**Virginia Tech, Dr. Robert Parker, r.parker@vt.edu**  
**McMaster University, Dr. Saeid Habibi, habibi@mcmaster.ca**  
**National Renewable Energy Laboratory (NREL), Dylan Cutler, Dylan.Cutler@nrel.gov**  
**Emerson (Browning), Don Sullivan, don.sullivan@emerson.com**  
**AMCA International (Mark DeRoo, mderoo@amca.org)**

Potential Co-funders (organization, contact person information):  
**AMCA International (Joe Brooks, jbrooks@amca.org)**  
**AHRI (Xudong Wang, xwang@ahrinet.org)**  
**Power Transmission Distributors Association (Ann Arnott, aarnott@ptda.org)**

(Three qualified bidders must be recommended, not including WS authors.)

- Is an extended bidding period needed?
- Has an electronic copy been furnished to the MORTS?
- Will this project result in a special publication?
- Has the Research Liaison reviewed work statement?

Yes	No	How Long (weeks)
<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<b>N/A</b>
<input type="checkbox"/>	<input type="checkbox"/>	
<input checked="" type="checkbox"/>	<input type="checkbox"/>	

\* Reasons for negative vote(s) and abstentions

\*\* Denotes WS author is affiliated with this recommended bidder  
Use additional sheet if needed.

**WORK STATEMENT#**

1769

**Title:**

Experimental Evaluation of the Efficiency of Belt Drives for Fans

**Sponsoring TC/TG/MTG/SSPC:**

TC 5.1 “Fans”

**Co-Sponsoring TC/TG/MTG/SSPCs (List only TC/TG/MTG/SSPCs that have voted formal support)**

N/A

**Executive Summary:**

This project involves testing to determine the efficiency characteristics of belt drives for fans, and developing a belt efficiency model covering full and part-load operation. This information is not available and is needed to support fan system selection decisions and future standards, codes, and regulations. The final report will include the experimental data and model. A technical paper will summarize research results.

**Applicability to the ASHRAE Research Strategic Plan:**

Goal #1 of the ASHRAE Research Strategic Plan is to “Maximize the actual operational energy performance of buildings and facilities.” The proposed research supports several needs identified in this goal including documenting actual energy savings and performance impacts for selected energy measures, documenting the impact of design alternatives, and developing more accurate methods to relate building energy simulation models to actual building energy use.

**Application of Results:**

The U.S. Department of Energy (DOE) is currently working toward regulation of fan efficiency [DOE 2015], most likely in terms of wire-to-air fan system efficiency, which includes the effects of fan, belt drive, motor, and variable-frequency-drive (VFD) efficiencies. AMCA International also has recently published a standard method of calculating overall wire-to-air fan system efficiency at a rating point, which is called AMCA 207 [AMCA 2017]. As stated in the purpose of AMCA 207: “While direct measurement of fan system performance is preferred, the large number of fan system configurations often makes testing impractical. This standard offers a standardized method to estimate fan system performance by modeling commonly used components. Calculations reported in accordance with this standard offer fan users a tool to compare alternative fan system configurations in a consistent and uniform manner.” It is expected that industry stakeholders (including AHRI, ASHRAE, and DOE) will rely on AMCA 207 to combine component performance to estimate fan system ratings and efficiency.

A commercially-available tool to estimate wire-to-air efficiency and to assess time-varying fan system performance over the course of a year is already available. More specifically, EnergyPlus, which is DOE’s flagship building energy simulation computer program, contains fan system component part-load models [DOE 2010]. They include a system curve (fan pressure rise) model (including the effects of system air leakage and duct static pressure reset), dimensionless fan efficiency and speed models, a belt model, and motor and VFD models. These models are more detailed than what AMCA 207 currently describes, because they are intended for time-dependent analyses (and integration of sub-hourly results to estimate annual performance).

While fan and motor efficiencies are well known, including their variation with load, and are readily available, part-load belt drive efficiencies are essentially not available (as stated in the “Background” section, which follows). In particular, the EnergyPlus belt part-load model is based on data for only one belt [Nadel et al. 2002]. The proposed research will provide more belt drive part-load efficiency data and an accurate model to support all of the efforts described above.

### **State-of-the-Art (Background):**

Belt drives have long been used to match fixed-pole motor speeds with fan speeds required to achieve operating airflows and pressure rises. With low investment cost, they provide torque and speed conversion that is adjustable in field installations. Although there is an increasing trend toward direct drive fans in many applications, it is recognized that the need for high efficiency belt drives remains especially for low speed fans that operate at high torque. For fans sold with 1 hp through 300 hp motors, a major commercial fan manufacturer (Greenheck Fan) reports that over 80% of these sales are belt driven.

Notched or synchronous belt drives are an alternative to conventional wrapped V-belt drives and provide better efficiency [DOE 2012, Gates 2014]. However, their disadvantages have outweighed their efficiency advantage resulting in the continued prominence of conventional V-belt drives.

Belt drive efficiency is generally defined as the power input to the fan pulley divided by the power output by the motor pulley. More specifically, because mechanical power in this case is the product of speed and torque, efficiency can be defined as [De Almeida and Greenberg 1995]:

$$\eta_{belt} = 100 \left( \frac{\omega_{fan} T_{fan}}{\omega_{motor} T_{motor}} \right) \quad \text{(Equation 1)}$$

where

- $\eta_{belt}$  = Belt drive efficiency, %
- $\omega_{fan}$  = Fan shaft rotational speed, rpm
- $T_{fan}$  = Net torque on fan shaft pulley, in-lb<sub>f</sub>
- $\omega_{motor}$  = Motor shaft rotational speed, rpm
- $T_{motor}$  = Net torque on motor shaft pulley, in-lb<sub>f</sub>

The net torque for each pulley is defined as the net belt pull (tangential force acting on the tight side of the belt minus the tangential force acting on the slack side) multiplied by the pulley pitch radius [Euler 1769, Lubarda 2015]. These forces are also speed dependent due to the rapidly increasing effects of centrifugal force on the belt as pulley speeds increase (centrifugal force varies with the shaft speed squared). Centrifugal forces also reduce the belt angle of contact for each pulley as the pulley speeds increase, which in turn can lead to increased slip [Faires 1965].

Belt drives have inherent bending and frictional losses at each pulley, which affect the drive forces and thus the net torque at the pulleys. Bending (hysteresis) losses are load (torque) *independent* while frictional losses are load *dependent*. Belts are also subject to slip- and creep-related speed losses. The latter occurs because the belt elongates differently at each pulley's entry and exit, which in turn causes the belt to "creep" around the pulleys and thus reduce the fan shaft speed. There are many design and operation variables that affect these losses and thus belt drive efficiency. They include: belt type and cross-section, pulley diameters, shaft to shaft distance, power delivered, and service (oversizing) factor [Kong 2003, Carlisle 1980].

As a result, belt drive efficiency depends on the specific design and operating point of the belt drive system. It also varies with belt loading and speed in variable-speed fan applications, when they operate at power levels significantly lower than the drives are designed to carry. Accurate and reliable information on fan belt drive efficiency at full-load (design) and part-load conditions is not generally available and the impact of the many variables that affect part-load efficiency is also not currently well known. It is also difficult to use fundamental engineering principles related to belt static and dynamic

loading to analytically determine belt drive efficiency. However, even though performance data for V-belt drives do not normally reference full vs. part load or operating conditions, they do provide maximum rated loads and service factors that can be used to indicate the actual loading in relation to this maximum rated load.

For example, AMCA 203 provides a rough estimate of V-belt drive losses at design capacity, but this estimate varies only with motor power and is based on a small number of tests conducted many years ago [AMCA 1990]. ISO 12759 has an entirely different estimate of drive efficiency that is more of a straight line approximation based on power [ISO 2010]. Recent controlled experiments have shown a strong correlation between transmission efficiency and output torque [Dereyne et al. 2013]. An unpublished experiment conducted at Lawrence Berkeley National Laboratory (LBNL) in 2013 is attached as Appendix A to illustrate that this effect is highly non-linear and that belt efficiency decreases substantially with speed and load.

#### **Advancement to the State-of-the-Art:**

As stated in the “Background” section, accurate and reliable information on fan belt drive efficiency at full-load (design) and part-load conditions is not generally available and the impact of the many variables that affect part-load efficiency is also not currently well known. The proposed research will provide more belt drive part-load efficiency data and an accurate model to support the efforts described in the “Application of Results” section. In turn, the research will enable more accurate estimates of actual energy savings and performance impacts for selected energy measures, documenting the impact of design alternatives, and developing more accurate methods to relate building energy simulation models to actual building energy use.

#### **Justification and Value to ASHRAE:**

The “Application of Results” section describes industry needs in terms of better understanding the role of individual components in fan system performance. In particular, the U.S. Department of Energy is working toward regulation of fan efficiency using a wire-to-air efficiency metric, which depends in part on belt part-load efficiency. Additionally, ASHRAE Energy Standards (e.g., Standard 90.1) are continuing to include fan efficiency requirements and state building codes likely will be adopting these requirements. The results of this research effort will provide tools to air system designers to allow them to separate out the impacts of belt part-load efficiency on system efficiency, to compare the efficiency levels of belt- and direct-driven fans, and to balance energy savings with other requirements used in the fan system selection process.

In the past, the work statement authors have spoken with belt drive manufacturers to gauge their interest in such a project (e.g., Browning, Carlisle). All have stated that they would be interested in participating, at least in an advisory role, and some perhaps as project bidders. AMCA International, the Air-Conditioning, Heating and Refrigeration Institute (AHRI), and the Power Transmission Distributors Association (PTDA) are stakeholders who may be willing to help fund this project. The bidder is encouraged to seek and propose cofunding, if possible. The proposal shall include a letter of commitment from each cofunder.

## **Objectives:**

The objectives of this project are to:

- Perform a review of available literature, articles, and previous testing of belt drive efficiency, including any existing formulas or algorithms for calculation of belt drive efficiency.
- Develop a method of test and test equipment characteristics that will ensure accurate test results over a belt drive power range of 1 to 100 hp.
- Determine experimental variables and outline a test program that will enable the impact of key variables on belt drive efficiency to be quantified at full and part-load.
- Conduct efficiency testing on fan belt drives covering the range of variables identified.
- Analyze results to establish the dependence of belt drive efficiency on the variables identified.
- Develop algorithms to predict full-load efficiency for belt drives along with the expected variation of efficiencies at part-load.

## **Scope/Technical Approach:**

This project involves lab testing, as well as data analyses and modeling.

Bidders on this work statement are expected to demonstrate expertise with measuring mechanical drive system efficiency, as well as shaft power, speed, and torque. Bidders should have a thorough understanding of fan system and belt drive design and applications.

### **Task 1: Identify, Review, and Analyze Existing Data Sources**

A literature search of recent research on drive belt efficiency testing and modeling will be carried out by the bidder and all pertinent references will be summarized. This review will include interviews with belt drive suppliers and fan manufacturers to determine typical drive selection tools and procedures. The search shall include research carried out in other industry sectors that might be applicable (e.g., the automotive and industrial sectors).

*Task 1 Deliverable:* Interim Report 1 containing a summary of all pertinent prior work from the literature. Documents referred to shall be listed in the form of an annotated bibliography that follows the summary. Unless otherwise specified, the report shall be furnished electronically for review by the PMS. The Contractor shall not proceed with the next tasks until Task 1 deliverables are approved by the PMS.

### **Task 2: Method of Test**

The test rig and equipment used must be selected to ensure accurate results covering the entire scope. Some of the variables tested in this project could have an impact on the accuracy of measurement. For example, some sensors used for measuring torque may be sensitive to radial or axial forces. Because some of the variables studied in this project will influence radial or axial forces, the torque sensing accuracy must be independent of these forces. For data acquisition and data reduction purposes, the location and types of transducers for measuring shaft speed and torque, as well the instruments used to assess belt drive tension and alignment, shall be proposed by the bidder for review and approval by the Project Monitoring Subcommittee (PMS).

A preliminary list of test variables (e.g., transmitted power, speed ratio, number of belts) shall be developed by the bidder based on the literature search for review and approval by the PMS. Sensitivity to each of these variables shall be evaluated by the bidder. Variables that appear to be significant shall be tested in more detail by the bidder and those determined to be insignificant will not be studied. In this way, preliminary sensitivity testing will dictate subsequent test planning. A test plan based on the selected variables shall be developed by the bidder for review and approval by the PMS.

*Task 2 Deliverable:* Interim Report 1 containing a description of the test equipment, preliminary and final test variable list, and test plan. Unless otherwise specified, the report shall be furnished electronically for review by the PMS. The Contractor shall not proceed with the next tasks until Task 2 deliverables are approved by the PMS.

### **Task 3: Testing**

For this project, new experimental data will need to be collected to supplement data that might be available in the literature. This task involves performance testing of belt drives for fans that covers a range of belt types (wrapped and notched), belt cross sections (A, AX, B, BX, 5VX), speeds, torques, drive ratios, and service factors that are commonly used in HVAC fan systems. Depending on the test variables selected in Task 2, the testing will likely cover 20 to 40 different belt and pulley combinations, all correctly aligned and tensioned according to belt manufacturer specifications.

A segment of the tests shall also be conducted at reduced speeds and torques to represent the variable loading of a fan in a typical variable-air-volume system and the reduction in belt drive efficiency at part load.

Additionally, the effect of belt tensioners (e.g., the Fenner Drives “T-Max” Tensioner) shall be tested, because they introduce additional bending and frictional losses that reduce drive efficiency.

Sufficient repetition of the test process shall be documented to satisfy the PMS that the test results are repeatable. The bidder shall propose a repeatability threshold and provide associated reasoning to support its selection so that the threshold can be used for test result review and approval by the PMS. All analyses shall include uncertainty estimates, which shall be conducted according to the rules described in the “Guide to the expression of uncertainty in measurement” [JCGM 2008].

*Task 3 Deliverables:* Interim Report 2 describing the test data and calculated efficiency results for each drive combination tested, including uncertainty estimates and their method of calculation. Unless otherwise specified, the report shall be furnished electronically for review by the PMS. The Contractor shall not proceed with the next task until Task 3 deliverables are approved by the PMS.

### **Task 4: Develop and Verify Model**

The test results will be used to develop two different models for belt drive efficiency. The first model shall provide an estimation of the efficiency for a specific drive configuration. Depending on which variables are identified as being most important, this specific configuration will include a number of variables such as the power transmitted, speed ratio, belt cross section, pulley diameters, and number of belts. This model is intended to be used as an aid in selecting and evaluating a specific drive combination for an application.

The second model shall estimate efficiencies for typical V-belt drives, independent of the specific drive configuration. AMCA 203 provides an example of such a model (as a possible starting point), because it uses a simple relationship between drive efficiency and power consumed. This general model shall be based on as few variables as possible while still providing reasonable accuracy. This model is intended to be used to estimate transmission efficiency for standards, codes, and regulations.

*Task 4 Deliverables:* Final report containing: a) The specific configuration model in the form of tables or charts covering the range of components tested. b) The general model as a mathematical function of the variables chosen. c) Expected deviations of the models relative to the measured data shall also be provided. The two interim reports describing the outcomes of Tasks 1 through 3 shall be included as report chapters.

The final report shall be in a form approved by the Society and shall be submitted to the Society's Manager of Research and Technical Services (MORTS) by the end of the Agreement term, containing complete details of all research carried out under this Agreement, including a summary of the project findings. Unless otherwise specified, the *draft* final report shall be furnished electronically for review first by the PMS. The Contractor shall not finalize the report until the draft is approved by the PMS.

Tabulated values for all measurements shall be provided as an appendix to the draft final report (for measurements that 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 sponsoring TC/TG, in their sole discretion, final copies of the final report will be provided by the Contractor 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.

**Deliverables/Where Results Will Be Published:**

Progress and Financial Reports, Technical Paper(s), Data, and Project Synopsis shall constitute the additional deliverables ("Additional 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 (MORTS) on or before each January 1, April 1, June 1, and October 1 of the contract period.

Furthermore, the Contractor'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 ASHRAE annual and winter meetings, and be available to answer such questions regarding the research as may arise.

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

One or more papers shall be submitted first to the 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 paper.

Technical or HVAC&R Research papers. The paper title shall contain the research project number (1769-RP) at the end of the title in parentheses.

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 MORTS first and not to the publication's editor or Program Committee.

c. Data

Data are defined in General Condition VI, "DATA", which is listed in the ASHRAE Research Manual [ASHRAE 2016]. In particular, the Contractor agrees to maintain true and complete books and records, including but not limited to notebooks, reports, charts, graphs, analyses, computer programs, visual representations etc., (collectively, the "Data"), generated in connection with the

Services. Society representatives shall have access to all such Data for examination and review at reasonable times. The Data shall be held in strict confidence by the Contractor and shall not be released to third parties without prior authorization from the Society, except as provided by General Condition VII, "PUBLICATION" in the Research Manual. The original Data shall be kept on file by the Contractor for a period of two years after receipt of the final payment and upon request the Contractor will make a copy available to the Society.

d. 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 MORTS by the end of the Agreement term for publication in ASHRAE Insights.

The Society may request that the Contractor 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:**

It is expected that this project will take 18 months to complete at a total cost of \$120,000, with at least 15% of the time (2.7 months) attributed to the Principal Investigator.

The funding listed is for labor and indirect costs. It is expected that the bidder will already have suitable test equipment to carry out the research, so the proposed budget does not include this cost. Also, it is anticipated that the bidder will arrange for pulleys and belts used for testing to be donated by manufacturers (i.e., as possible co-funding), and the proposed budget does not include this cost.

**Proposal Evaluation Criteria:**

No.	Proposal Review Criterion	Weighting Factor
1	Contractor's understanding of the Work Statement as revealed in the proposal.	20%
2	Quality of testing facility and methodology proposed for conducting research: a. Proposed test facility. b. Proposed methodology. c. Data collection and analysis techniques.	30%
3	Qualification of personnel for this project: a. Experience with mechanical drive system testing. b. Experience with fan system design and belt drive mechanics. c. Time commitment of principal investigator. d. Other team members' qualifications.	30%

4	<p>Organization:</p> <p>a. Detailed work plan with major tasks and key milestones.</p> <p>b. All technical and logistic factors considered.</p> <p>c. Reasonableness of project schedule.</p>	15%
5	Performance of contractor on prior ASHRAE projects (no penalty for new contractors).	5%

**Project Milestones:**

No.	Major Project Completion Milestone	Months from Project Start
1	Interim Report 1 documenting literature review, test equipment, test variables, and test plan (Tasks 1 and 2)	6
2	Interim Report 2 documenting test results, uncertainty estimates, and calculation methods (Task 3)	12
3	Final Report documenting models and expected deviations from measured data (Task 4), along with complete details of all research carried out under the Agreement.	18

**Authors:**

Tim Mathson (Greenheck Fan), Craig Wray (Retired)

**References:**

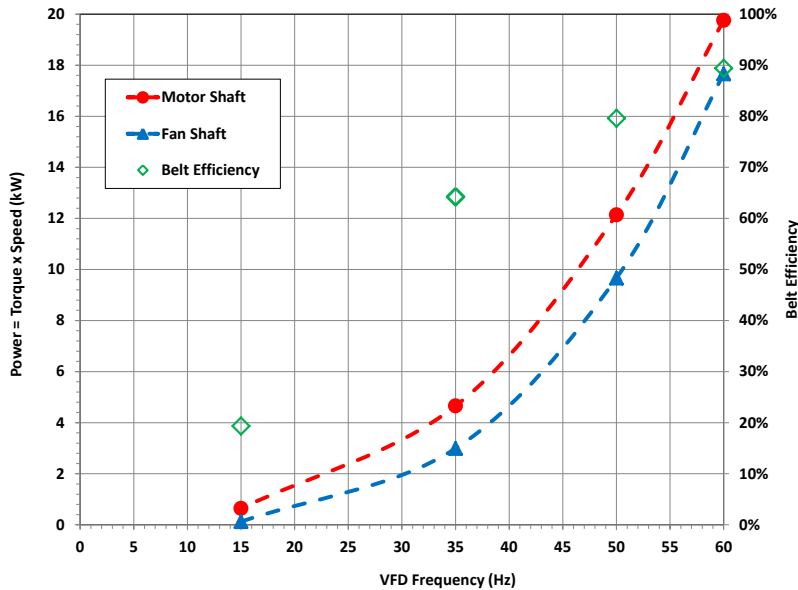
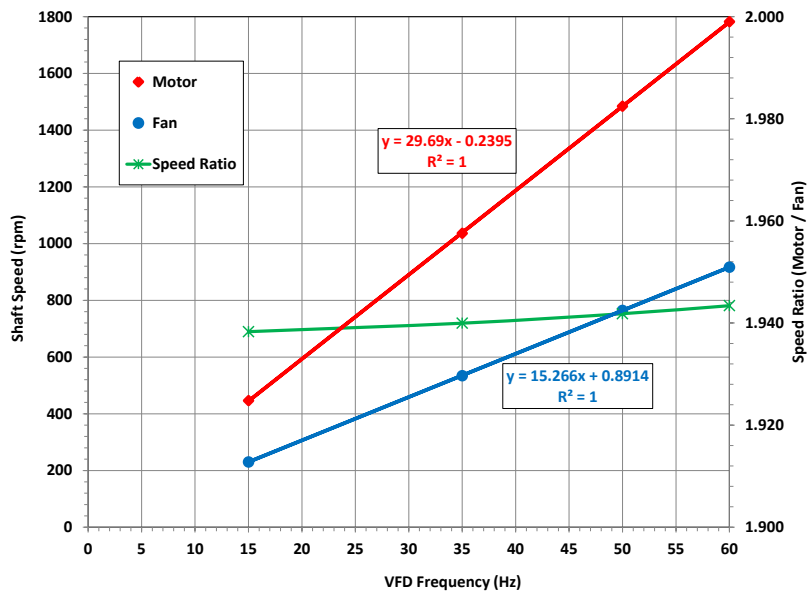
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**Appendix A: Preliminary V-Belt Drive Test Results [LBNL 2013, Unpublished]**

**Tested System:** Centrifugal DWDI backward-inclined fan (Aladdin Type BB Size 365) driven by 30 hp variable-speed electric motor (rated at 1770 rpm); shaft to shaft centerline span: 48.75 in.; pulleys are three-groove Browning Q-D types: 3B184SK (fan, 18.75 in. OD) and 3B94SK (motor, 9.75 in. OD), aligned (angular, parallel, and offset) using reflective laser optical system; each of three V-belts is Gates Hi-Power II B139 V80, initial tension set to manufacturer specifications using deflecting belt tension gauge and confirmed with sonic tension meter

**Measurement Equipment:** Fan shaft and motor shaft torque and speed measured using two Sensor Developments Inc. pulley torque and speed meters (custom-made, factory-calibrated); modified pulley hubs each include strain gauge; associated shaft-end-mounted stationary instrument package connected to strain gauge through slip rings and includes optical speed encoder; sensor outputs recorded using Fluke 289 digital logging multimeter.





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Manager Research & Technical Services

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TO: Zvirimumwoyo Chinoda, Chair TC 5.1, [zpchinoda@revcor.com](mailto:zpchinoda@revcor.com)  
Brian Reynolds, Research Subcommittee Chair TC 5.1, [breynolds@trane.com](mailto:breynolds@trane.com)

CC: David John, Research Liaison 5.0, [davidjohntarpon@gmail.com](mailto:davidjohntarpon@gmail.com)

FROM: Michael Vaughn, MORTS, [mvaughn@ashrae.org](mailto:mvaughn@ashrae.org)

DATE: July 19, 2016

SUBJECT: Research Topic Acceptance Request (1769-RTAR), Experimental Evaluation of the Efficiency of Belt Drives for Fans

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During their annual meeting, the Research Administration Committee (RAC) reviewed the subject Research Topic Acceptance Request (RTAR) and voted to accept with comments it for further development into a work statement (WS) provided that the two approval comment(s) below are addressed to the satisfaction of your Research Liaison in a revision to the RTAR.

1. How much the percentage of belt drives are used, compared with direct drives in US market?
2. The RTAR does not reference any consideration of existing formulas or algorithms for calculation of belt drive efficiency/losses.
3. The RTAR presents a rationale that drive efficiency will be different at part load conditions. Belts do not have a full load condition and a part load condition like a chiller for example. Fan belt drives simply connect two pulleys that rotate at different speeds.

Please coordinate changes to the RTAR with the help of your Research Liaison, David John, [davidjohntarpon@gmail.com](mailto:davidjohntarpon@gmail.com), or in response to the approval comment(s) only so that the revised RTAR can be submitted to the Manager of Research and Technical Services and posted by ASHRAE as part of the Society's Research Implementation Plan.

Once the revised RTAR is posted, please develop a work statement also with the help of your Research Liaison prior to submitting it to the Manager of Research and Technical Services for consideration by RAC. The work statement must be approved by the Research Liaison prior to submitting it to RAC.

An RTAR evaluation sheet is attached as additional information and it provides a breakdown of comments and questions from individual RAC members based on specific review criteria. This should give you an idea of how your RTAR is being interpreted and understood by others. Some of these comments may indicate areas of the RTAR and subsequent WS where readers require additional information or rewording for clarification.

The first draft of the work statement should be submitted to RAC no later than **May 15, 2018** or it will be dropped from display on the Society's Research Implementation Plan. The next likely submission deadline for work statements is **December 15, 2016** for consideration at RAC's 2017 winter meeting. The submission deadline after that for work statements is **May 15, 2017** for consideration at the RAC's 2016 Annual meeting.

<b>Project ID</b>	<b>1769</b>	
<b>Project Title</b>	Experimental Evaluation of the Efficiency of Belt Drives for Fans	
<b>Sponsoring TC</b>	TC 5.1, Fans	
<b>Cost / Duration</b>	\$100,000 - \$120,000/ 12 to 18 months	
<b>Submission History</b>	2nd RTAR Submission - 1st Submission rejected by RAC June 2015	
<b>Classification: Research or Technology Transfer</b>	Technology Transfer	
<b>RAC 2016 Annual Meeting Review</b>		
<b>Essential Criteria</b>	<b>Voted NO</b>	<b>Comments &amp; Suggestions</b>
<b>Background:</b> The RTAR should describe current state of the art with some level of literature review that documents the importance/magnitude of a problem. References should be provided. If not, then note it in your comments.	15	#2- Belt drives are used in many mechanical engineering applications, for examples, in automobiles, are there any suitable data which are applicable to HVAC systems? #7 - It is surprising that such data is not available in other industries, for example, automotive industry. Authors are strongly recommended to include detailed literature survey from other industries into the work statement. It is also recommended to develop a first project just for literature review before conducting any experiments. #15 - I don't feel that they presented existing available formulas and other information (tables/graphs) that can currently be used to calculate belt efficiency.
<b>Research Need:</b> Based on the background provided is the need for additional research clearly identified? If not, then the RTAR should be rejected.	15	#2 - The research topic are not specialized for HVAC industry, other mechanical engineering feels can do it.
<b>Relevance and Benefits to ASHRAE:</b> Evaluate whether relevance and benefits are clearly explained in terms of: a. Leading to innovations in the field of HVAC & Refrigeration b. Valuable addition to the missing information which will lead to new design guidelines and valuable modifications to handbooks and standards. Is this research topic appropriate for ASHRAE funding? If not, Reject.	15	PW - It is valuable addition/extension/verification of the information that exists
<b>IF ABOVE THREE CRITERION ARE NOT ALL SATISFIED - MARK "REJECT" BELOW &amp; CONTINUE REVIEW BELOW</b>		
<b>Other Criteria</b>	<b>Voted NO</b>	<b>Comments &amp; Suggestions</b>
<b>Project Objectives:</b> Based on the background and need, evaluate whether the project objectives are: 1. Aligned with the need 2. Specific 3. Clear without ambiguity 4. Achievable If not, then appropriate feedback should be provided.	10	#10- The Project Objectives section has items that might be better located under Approach. From what they say, the real objective appears to be to provide a standardized method to compare belt vs. direct drive fans at various motor sizes and loading. This should be clearer. #7 - It seems the range of 1 to 100 HP is quite large. Not sure why there is a need to test such a wide range for practical applications in HVAC. It is required that feedback and contributions from sponsoring TC 4.7 should be included in the work statement and not state just a sponsoring TC.
<b>Expected Approach and Budget:</b> Is there an adequate description of the approach in order for RAC to be able to evaluate the appropriateness of the budget? If not, then the RTAR should be returned for revision. Anticipated funding level and duration:		#7 - It sees the manner in which the budget is stated indicates Mr. Wray has already the required lab setup and mostly likely will be a bidder on this project. It is strongly recommended to arrange cofunding before writing the work statement.
<b>References:</b> Are the references provided?		
<b>Decision Options</b>	<b>Initial Decision?</b>	<b>Final Approval Conditions</b>
ACCEPT AS-IS		#2 - How much the percentage of belt drives are used, compared with direct drives in US market? It will show us the importance of the study for attaining the nationwide energy efficiency. #7 - See above #4 - The Authors will seek collaboration with the Industry and such collaboration is recommended when WS is being developed.
ACCEPT W/COMMENTS		#15 - I don't feel they established the need or the level of benefit. It would be impossible to predict tension for a given application so this is at best a rough estimate no matter how many other variables are considered. It would be beneficial if data was presented to indicate just how much variation in efficiency (generally assumed to be 3%-5%) there is expected to be. <b>ADDITIONAL COMMENTS:#15- Reliance on Existing Belt Drive Efficiency/Losses Information: The RTAR does not reference any consideration of existing formulas or algorithms for calculation of belt drive efficiency/losses. Most RAC members were aware that there are existing formulas, tables , and other information that is used both in the HVAC industry and other industries (such as automotive). The RTAR seems to</b>
REJECT		

**ACCEPT Vote** - Topic is ready for development into a work statement (WS).

**ACCEPT W/COMMENTS Vote** - Minor Revision Required - RL can approve RTAR for development into WS without going back to RAC once TC satisfies RAC's approval condition(s)

**REJECT Vote** - Topic is not acceptable for the ASHRAE Research Program

**Research Topic Acceptance Request Cover Sheet**

Date: **9 March 2016**

(Please Check to Insure the Following Information is in the RTAR)

- A. Title
- B. Executive Summary
- C. Background
- D. Research Need
- E. Project Objectives
- F. Expected Approach
- G. Relevance and Benefits to ASHRAE
- H. Anticipated Funding Level and Duration
- I. References

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Title:  
**Experimental Evaluation of the Efficiency of Belt Drives for Fans**

RTAR # **1769**  
 (To be assigned by MORTS)

Results of this Project will affect the following Handbook Chapters, Special Publications, etc.:  
**Systems & Equipment S21, S45**

Research Classification:

- Basic/Applied Research
- Advanced Concepts
- Technology Transfer

<input checked="" type="checkbox"/>
<input type="checkbox"/>
<input type="checkbox"/>

Responsible Committee: **TC 5.1 "Fans"**

Date of Vote: **3/29/2016**

For		<b>11</b>
Against	*	<b>0</b>
Abstaining	*	<b>0</b>
Absent or not returning Ballot	*	<b>3</b>
Total Voting Members		<b>14</b>

RTAR Authors

Lead: **Tim Mathson**  
 Others: **Craig Wray**

Co-sponsoring TC/TG/MTG/SSPCs (give vote and date)

**TC 4.7 Modeling**

Expected Work Statement Authors

Lead: **Tim Mathson, Brian Reynolds**  
 Others: **Craig Wray**

Potential Co-funders (organization, contact person information):

**AMCA International  
 AHRI  
 Rubber Manufacturers Association**

- Has an electronic copy been furnished to the MORTS?
- Has the Research Liaison reviewed the RTAR?

Yes	No
<input checked="" type="checkbox"/>	<input type="checkbox"/>
<input checked="" type="checkbox"/>	<input type="checkbox"/>

\* Reasons for negative vote(s) and abstentions

**RTAR # 1769**

**Title:**

*Insert proposed project title: Experimental Evaluation of the Efficiency of Belt Drives for Fans*

**Executive Summary**

*Describe in summary form the proposed research topic, including what is proposed, why this research is important, how it will be conducted, and why ASHRAE should fund it (50 words maximum)*

This project involves testing to determine the efficiency characteristics of belt drives for fans, and developing a belt efficiency model covering full and part-load operation. This information is not available and is needed to support fan system selection decisions and future standards, codes, and regulations. The final report will include the experimental data and model. A technical paper will summarize research results.

**Background**

*Provide the state of the art with key references (at the end of this document) substantiating it (300 words maximum)*

Belt drives have long been used to match fixed-pole motor speeds with fan speeds required to achieve \_\_\_ operating airflows and pressure rises. With low investment cost, they provide torque and speed conversion that is adjustable in field installations. Although there is an increasing trend toward direct drive fans in many applications, it is recognized that the need for high efficiency belt drives remains especially for low speed fans that operate at high torque.

Belt drives have inherent bending and frictional losses that must be quantified in order to accurately assess their utility. Notched or synchronous belt drives are an alternative to conventional wrapped V-belt drives and provide better efficiency [1,2]. However, their disadvantages have outweighed their efficiency advantage resulting in the continued prominence of conventional V-belt drives.

Accurate and reliable information on fan belt drive efficiency at part-load is not available and is difficult to determine analytically using fundamental engineering principles related to belt static and dynamic loading. In particular, there are many variables that impact belt drive efficiency such as belt type and cross-section (related to bending), power delivered, speed ratio, and service factor [3,4]. For example, variable-speed fan applications result in operation at power levels significantly lower than the drives are designed to carry. The impact of these variables on belt part-load efficiency is not currently well known. AMCA 203 provides a rough estimate of V-belt drive losses at *design* capacity, but this estimate varies only with motor power and is based on a small number of tests conducted many years ago [5]. ISO 12759 has an entirely different estimate of drive efficiency that is more of a straight line approximation based on power [6]. Recent controlled experiments have shown a strong correlation between transmission efficiency and output torque [7]. An unpublished experiment conducted by Craig Wray at Lawrence Berkeley National Laboratory in 2013 is attached in Appendix A to illustrate that this effect is highly non-linear and that belt efficiency decreases substantially with speed and load.

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## Research Need

*Use the state of the art described above as a basis to specify the need for the proposed effort (250 words maximum)*

The U.S. Department of Energy (DOE) is currently working toward regulation of fan efficiency [8], most likely in terms of *wire-to-air fan system efficiency*, which includes the effects of fan, belt drive, motor, and variable-frequency-drive (VFD) efficiencies. AMCA International is also currently working on a standard method of calculating overall wire-to-air fan system efficiency at a *rating point*, which is called AMCA 207 [9]. As stated in the purpose of the current 207 draft: “While direct measurement of fan system performance is preferred, the large number of fan system configurations often makes testing impractical. This standard offers a standardized method to estimate fan system performance by modeling commonly used components. Calculations reported in accordance with this standard offer fan users a tool to compare alternative fan system configurations in a consistent and uniform manner.” It is expected that industry stakeholders (including AHRI, ASHRAE, and DOE) will rely on AMCA 207 to combine component performance to estimate fan system ratings and efficiency.

A commercially-available tool to estimate wire-to-air efficiency and to assess time-varying fan system performance *over the course of a year* is already available. More specifically, EnergyPlus, which is DOE’s flagship building energy simulation computer program contains fan system component part-load models [10]. They include a system curve (fan pressure rise) model (including the effects of system air leakage and duct static pressure reset), dimensionless fan efficiency and speed models, a belt model, and motor and VFD models. These models are more detailed than what AMCA 207 currently has proposed, because they are intended for time-dependent analyses (and integration of sub-hourly results to estimate annual performance).

While fan and motor efficiencies are well known, including their variation with load, and are readily available, part-load belt drive efficiencies are essentially not available (as stated in the “Background” section). In particular, the EnergyPlus belt part-load model is based on data for only one belt [11]. The proposed research will provide more belt drive part-load efficiency data and an accurate model to support all of the efforts described above.

### Project Objectives

*Based on the identified research need(s), specify the objectives of the solicited effort that will address all or part of these needs (150 words maximum)*

The objectives of this project will be to:

- Perform a review of available literature, articles, and previous testing of belt drive efficiency.
- Develop a method of test and test equipment characteristics that will ensure accurate test results over a belt drive power range of 1 to 100 hp.
- Determine experimental variables and outline a test program that will enable the impact of key variables on belt drive efficiency to be quantified at full and part-load.
- Conduct efficiency testing on fan belt drives covering the range of variables identified.
- Analyze results to establish the dependence of efficiency on the variables identified.
- Develop algorithms to predict full-load efficiency for belt drives along with the expected variation of efficiencies at part-load.

### Expected Approach

*Describe in a manner that may be used for assessment of project viability, cost, and duration, the approach that is expected to achieve the proposed objectives (200 words maximum).*

*Check all that apply: Lab testing , Computations , Surveys , Field tests , Analyses and modeling , Validation efforts , Other  (specify)*

Conduct performance testing of belt drives for fans that covers a range of belt types (wrapped and notched), belt cross sections (A, AX, B, BX, 5VX), speeds, torques, drive ratios, and service factors that are commonly used in HVAC fan systems. This testing will likely cover 20 to 40 different belt and pulley combinations, all correctly aligned and tensioned according to belt manufacturer specifications. A segment of these tests will also be conducted at reduced speeds and torques to represent the variable loading of a fan in a typical variable-air-volume system and the reduction in belt drive efficiency at part load. Additionally, the effect of belt tensioners (e.g., the Fenner Drives "T-Max" Tensioner) will be tested, because they introduce additional bending and frictional losses that reduce drive efficiency.

### Relevance and Benefits to ASHRAE

*Describe why this effort is of specific interest to ASHRAE, its impact, and how it will benefit ASHRAE and the society. How does it align with ASHRAE Strategic Plans and Initiatives? How does it advance the state of the art in this area in general? Are there other stakeholders that should be approached to obtain relevant information or co-funding? (350 words maximum)*

The “Research Need” section describes industry needs in terms of better understanding the role of individual components in fan system performance. In particular, the U.S. Department of Energy is working toward regulation of fan efficiency using a wire-to-air efficiency metric, which depends in part on belt part-load efficiency. Additionally, ASHRAE Energy Standards (e.g., Standard 90.1) are continuing to include fan efficiency requirements and state building codes likely will be adopting these requirements. The results of this research effort will provide tools to air system designers to allow them to separate out the impacts of belt part-load efficiency on system efficiency, to compare the efficiency levels of belt- and direct-driven fans, and to balance energy savings with other requirements used in the fan system selection process.

Goal #1 of the ASHRAE Research Strategic Plan is to “Maximize the actual operational energy performance of buildings and facilities.” The proposed research supports several needs identified in this goal including documenting actual energy savings and performance impacts for selected energy measures, documenting the impact of design alternatives, and developing more accurate methods to relate building energy simulation models to actual building energy use.

In the past, the RTAR authors have spoken with belt drive manufacturers to gauge their interest in such a project (e.g., Browning, Emerson, Carlisle). All have stated that they would be interested in participating, at least in an advisory role, and some perhaps as project bidders. AMCA International, AHRI, and the Rubber Manufacturers Association are stakeholders who may be willing to help fund this project.

### Anticipated Funding Level and Duration

Funding Amount Range: \$100K-120K\*

Duration in Months: 12-18

- \* The funding listed is for labor and indirect costs. It is expected that the bidder will already have suitable test equipment to carry out the research, so the proposed budget does not include this cost. Also, it is anticipated that pulleys and belts used for testing will be donated by manufacturers (i.e., as possible cofunding), and the proposed budget does not include this cost.

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**Appendix A: Preliminary V-Belt Drive Test Results: 20 February 2013, Craig Wray, P.Eng.**

**Tested System:** Centrifugal DWDI backward-inclined fan (Aladdin Type BB Size 365) driven by 30 hp variable-speed electric motor (rated at 1770 rpm); pulleys are three-groove Browning Q-D types: 3B184SK (fan, 18.75 in. OD) and 3B94SK (motor, 9.75 in. OD), aligned (angular, parallel, and offset) using reflective laser optical system; each of three V-belts is Gates Hi-Power II B139 V80, initial tension set to manufacturer specifications using deflecting belt tension gauge and confirmed with sonic tension meter; shaft to shaft centerline span: 48.75 in.

**Measurement Equipment:** Fan shaft and motor shaft torque and speed measured using two Sensor Developments Inc. pulley torque and speed meters (custom-made, factory-calibrated); modified pulley hubs each include strain gauge; associated shaft-end-mounted stationary instrument package connected to strain gauge through slip rings and includes optical speed encoder; sensor outputs recorded using Fluke 289 digital logging multimeter.

