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**Work Statement**  
**TC/TG: 7.5 Smart Building Systems**

**Title:** Fault Detection and Diagnostics for Centrifugal Chillers - Phase III: Online-Time Implementation

**Executive Summary:** The objective of this project is to evaluate the effectiveness of fault detection and diagnostic (FDD) methods for electrically driven centrifugal chillers and to produce a specification for an algorithm that could be incorporated within commercial products. The proposed project is the final phase of a three-phase project involving the development, evaluation and laboratory and field testing.

**Applicability to ASHRAE Research Strategic Plan:** The proposed project addresses several goals of the ASHRAE Research Strategic Plan:

- D1 Establish techniques to improve the energy efficiency and reliability of heating, ventilating, cooling, and refrigeration system components.
- D5 Develop reliable, durable, and self-correcting sensor technology for monitoring indoor environmental quality, pollutants, energy conservation, and fault detection and diagnosis.
- E1 Make the results of ASHRAE sponsored and cooperative research available to the technical community.

The project makes a clear and direct contribution to goals D1 and D5, providing online detection and diagnosis of chiller faults. The methods developed under the project offer the potential to improve reliability and energy efficiency of the centrifugal chillers. Publication of the results will enhance member education.

**Application of Results:**

The handbook currently does not address fault detection and diagnostics (FDD). However, TC 7.5 has developed material for inclusion in Chapter 38 of Applications Handbook (TC 7.3). In addition, TC 7.5 is considering a new chapter focused on FDD for the next version of the Applications Handbook. The results of this research along with 1043-RP "Fault Detection and Diagnostic Requirements and Evaluation Tools for Chillers-Phase I" and 1275-RP "Evaluation and Assessment of Fault Detection and Diagnostic Methods for Centrifugal Chillers-Phase II" will be included in the FDD chapter (or section) in the handbook.

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

A significant portion of the energy (over 28% of the total cooling energy consumption is attributed to chillers and district cooling – Katipamula and Gaines 2003) and maintenance costs for operating commercial HVAC systems is associated with chillers. Although current control systems typically monitor many variables, the monitored information is seldom used for detecting and diagnosing faults or improper operations. At best, these systems incorporate automatic shutdown procedures that guard against catastrophic failure.

Automated fault detection and diagnostics (FDD) for HVAC systems in general and chillers in particular, has the potential to reduce energy and maintenance costs and improve comfort and reliability. Inadequate maintenance can lead to inefficient operation (energy costs), a loss in cooling capacity (comfort), and increased wear of components (reliability). However, excessive maintenance leads to unnecessary costs. In addition, early diagnosis of equipment problems can reduce the costs associated with repairs by improving scheduling and reducing on-site labor time.

The proposed work statement is the final phase of a three-phase project involving the development, evaluation and laboratory and field testing of FDD methods for centrifugal chillers. The first phase (1043-RP, Comstock et al., 1999) consisted of: 1) identification of the most important faults for centrifugal chillers based upon frequency of service and costs; 2) development of a database of chiller performance for normal operation and with faults at different levels of severity; and 3) development of a transient chiller model that can predict the effects of faults on performance. The second phase (1275-RP) was initiated to evaluate the effectiveness and robustness of at least four promising FDD methods using the tools developed under Phase I. A methodology for assessing performance of FDD methods was also developed in Phase II. The proposed work statement is aimed at performing real-time laboratory and field testing of the FDD method(s) recommended in Phase II in order to ascertain the performance of the tools under non-ideal conditions. The primary outcome of Phase III will be a proven and tested chiller FDD algorithm. Manufacturers and end-users will be able to take the algorithm and incorporate it into a commercial product.

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

The development of FDD methods for HVAC applications has been an active area of research over the past decade. A significant amount of work has been performed for vapor-compression equipment; however, given their importance from a standpoint of comfort and energy use, there have been relatively few studies specifically aimed at chillers. Peitsman and Bakker (1996), Stylianou and Nikanpour (1996), and Bailey (1998) developed and tested FDD methods for chillers; however, each study was limited to a single chiller tested in a laboratory environment. Laboratory testing is an important aspect of the development of FDD methods because it enables controlled testing over a range of conditions; however, it is not adequate for proving the robustness of new technologies such as FDD methods. To garner buy-in from controls and equipment manufacturers, prototype software that implements the FDD method needs to be tested with field data, preferably from a large sample of units over a broad range of operating conditions. The proposed project represents a significant increase in rigor over laboratory testing alone by requiring that field-testing be performed on at least three chillers for at least one complete chiller season.

Outcomes from the proposed research will contribute to the field of FDD for chillers through:

1. online testing of a computer-implemented chiller FDD method(s) in a laboratory setting that enables the introduction of the faults to be considered in a reproducible manner and under reproducible operating conditions;
2. the development and implementation of improvements to the chiller FDD method(s) stemming from the laboratory testing;
3. field-testing of the chiller FDD method(s); and
4. the development of a specification for a chiller FDD method(s) that is suitable for incorporation within a commercial system.

It is envisioned that by the end of Phase III, an algorithm(s) will be specified that could be incorporated within commercial products.

#### Justification and Value to ASHRAE:

The rigorous laboratory and field-testing work proposed in this project will help speed the commercialization of chiller FDD technology, thereby benefiting building owners, facility managers, operators, and occupants by helping ensure buildings are comfortable, sustainable and energy efficient. The main benefit to the ASHRAE membership will be a major step in the

testing and evaluation of one or more methods that, when implemented in new and existing chillers, will detect and diagnose operating faults before they become problems, thereby reducing maintenance costs, energy costs and occupant discomfort associated with the improper operation. Potential energy savings associated with better detection and diagnosis of faults are estimated to be about \$300 million annually in the U.S.<sup>1</sup>.

#### Objectives:

The objective of this project is to evaluate the effectiveness of one or more **electrically** driven chiller FDD methods and to produce a specification for an algorithm that could be incorporated within commercial products. First, the methods will be evaluated online in a laboratory environment, followed by evaluation in the field. The methods to be tested and procedures for conducting the evaluation were determined from Phase II research project 1275-RP.

#### Scope:

The following tasks are to be performed by the successful contractor. Additional specific information that is to be included in proposals is listed in the section titled **Other Information for Bidders**.

The bidder will evaluate two different chiller FDD methods in both the laboratory and in the field. The evaluation will be based on online implementation of the chosen method. The bidder is required to evaluate on the two methods recommended from RP-1275: 1) the heuristic rule-based approach<sup>2</sup> or 2) multiple linear regression model based approach<sup>3</sup>. If the bidder evaluates only one of the two recommended methods, the bidder is required to propose an alternate second method for testing. If the bidder selects an alternate second method, the bidder should provide a description of the method and justification of selection.

A list of faults that are to be instigated in the laboratory environment should be defined by the contractor. The previous ASHRAE research projects as well as several published papers have considered several faults during their investigation. The contractor should show understanding of this issue by selecting only those which are of primary concern (such as excess energy use, loss of cooling capability, increased maintenance) rather than blindly adopting the entire list of faults. This will be one of the evaluation criteria.

The major outcome of this research project is a specification of one or more algorithms for FDD of centrifugal chillers online that can be incorporated in commercial products or embedded into the control systems onboard the chiller. This will be accomplished through:

1. online testing of a computer-implemented chiller FDD method(s) in a laboratory setting that enables the introduction of the faults to be considered in a reproducible manner and under reproducible operating conditions;
2. the development and implementation of improvements to the chiller FDD method(s) stemming from the laboratory testing;
3. field-testing of the chiller FDD method(s) on three field chillers.

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<sup>1</sup> From US. Energy Information Administration data, central chillers serve 25% of the commercial-building floor area and consume about 0.3 Quad of primary energy. Assuming a power plant conversion efficiency of 33%, cooling equipment consumes 30 TWh of electricity. A savings of 10% attributable to diagnostics is worth \$300M at \$0.10/kWh.

<sup>2</sup> Refer to FDD#1 in RP-1275 final report for more details on the method.

<sup>3</sup> Refer to FDD#2 in RP-1275 final report for more details on the method.

### **Task 1: Develop Laboratory and Field Test Protocol**

As part of this task the contractor will develop a detailed laboratory and field testing protocol for evaluating the chosen methods online on a centrifugal chiller. The contractor shall review reports of ASHRAE research project from 1043-RP “Fault Detection and Diagnostic Requirements and Evaluation Tools for Chillers” to understand the instrumentation requirements and the methods used to validate the experimental data (Comstock and Braun 1999a, 1999b; and Comstock et al. 1999). In addition, the contractor shall also review the final report from 1275-RP “Evaluation and Assessment of Fault Detection and Diagnostic Methods for Centrifugal Chillers-Phase II” to get a better understanding the FDD methods and the evaluation process used to evaluate various FDD methods. One of the major conclusions of RP1275 was that among the four FDD methods evaluated, the heuristic rule-based approach along with a fault table (Chen and Braun 2001) and the model based approach involving regression model innovations with fault table (Li and Braun 2003) were the most promising. The contractor can pick both these FDD methods for evaluation or select one from these two (with justification) in conjunction with another FDD method (again, justification and reference to published work is required). Also, RP1275 identified certain improvements to the lab testing protocol adopted in RP1043. The contractor should show understanding of this aspect, and frame the experimental protocol accordingly.

After the protocol is developed by the contractor it must be reviewed and approved by the Program Monitoring Subcommittee (PMS). The PMS will make a decision on the approval no later than 6-weeks from the submission of the draft report describing the protocol.

### **Task 2: Laboratory Testing of the Selected Methods**

As part of this task the contractor will test and evaluate the selected FDD method(s) in the laboratory environment. Testing will include the introduction of the faults to be considered in a reproducible manner and under reproducible operating conditions. This task will begin only after the testing protocol is approved by the PMS (Task 1). Check the section titled “**Other Information to the Bidders**” for more information that should be included in the bid. A list of faults that are to be instigated include: 1) condenser fouling, 2) evaporator fouling, 3) loss of refrigerant, 4) excessive refrigerant, 5) condensable (nitrogen) in the system, 6) loss in condenser flow rate, 7) loss in evaporator flow rate and 8) excess oil.

If the contractor intends to instigate additional faults, they should be listed in the proposal. The contractor is required to document among other details the severity level at which the fault was first detected (i.e. the degradation of COP and/or cooling capacity).

### **Task 3: Field Testing of the Selected Methods**

As part of this task the contractor will test and evaluate the selected FDD method(s) in the field. The field testing should be conducted on **three** different chillers. Check the section titled “**Other Information to the Bidders**” for more information that should be included in the bid. Although it may be difficult to instigate faults in the field, but if the contractor intends to instigate faults in the field it should be noted in the proposal.

During testing of the selected FDD methods, if pre-existing faults are detected, the contractor is should verify the faults and if possible correct it. After the correction, the FDD method should be used to validate that the fault has been corrected. The contractors are required to describe how they intend to implement this process in the proposal.

### **Task 4: Specification of Algorithm for Incorporation into a Commercial System**

A detailed software specification for the selected algorithms will be developed as part of this task after the completion of the testing in laboratory and in the field.

### **Task 5: Document the Results in a Final Report**

The contractor shall provide the test protocol document, laboratory test results document and selected data sets, field test results document and selected data sets, a detailed software specification for the selected FDD method(s), of the a comprehensive final report that describes all the work undertaken in the project, and the prototype software tool used in testing the FDD methods in both the laboratory and field environment.

### **DELIVERABLES**

- Task 1 report that describes the laboratory and field test protocol.
- Task 2 report describing the testing of the FDD method(s) in the laboratory environment.
- Task 3 report describing the testing of the FDD method(s) in the field environment.
- Prototype software tool used in testing the FDD methods online in real-time and selected data sets from both laboratory and field tests. This should include the source code and executables for all software components.
- Progress and financial reports shall be made to the society through the Manager of Research at quarterly intervals; specifically on or before each January 1, April 1, June 1 and October 1 of the contract period. In addition, the following will be submitted:
  - Itemization of research and development needs relating to design and application of distributed generation systems incorporating intelligent control strategies.
  - 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.
- A Final Report.
  - A written 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 and as described under Task 6 above. The final report shall also include:
    - An Executive Summary suitable for wide distribution to the industry and to the public.
    - A section on "Utilization", to include: ASHRAE Handbook volume(s) and chapter(s) to which the research is related.
    - Aspects of the research confirming present knowledge or extending present knowledge. Suggestions for changes in the Handbook attributed to the research conducted. Suggestions for further research identified through the completed work. Unless otherwise specified, six copies of the final report shall be furnished for review by the Society's Project Monitoring Subcommittee (PMS).

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 bound copies
  - One unbound copy, printed on one side only, suitable for reproduction.
  - Two copies on disks; one in PDF format and one in Microsoft Word.
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- Technical Paper - 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 presentation at a Society meeting. The Technical Paper(s) shall conform to the instructions posted in “Manuscript Central” for a technical paper. The technical paper title shall contain the research project number (xxxx-RP) at the end of the title in parentheses, e.g., (9999-RP).
  - Data - Data is defined in General Condition VI, “DATA”

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.

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

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

#### **LEVEL OF EFFORT**

The expected level of effort for each phase and task are

Task 1 \$10,000

Task 2 \$60,000

Task 3 \$100,000

Task 4 \$15,000

Task 5 \$15,000

**Project \$200,000 total completed in 24 months**

**Total Effort:** 20 FTE person-months, of which 6 are for the principal investigator.

#### References:

Bailey, M.B. 1998. *The Design and Viability of a Probabilistic Fault Detection and Diagnosis Method For Vapor Compression Cycle Equipment*, Ph.D. Thesis, Department of Civil, Environmental, and Architectural Engineering, University of Colorado at Boulder.

Comstock, M. C., B. Chen, and J.E. Braun. 1999. *Literature Review for Applications of Fault Detection and Diagnostic Methods to Vapor Compression Cooling Equipment*. Ray W. Herrick Laboratories. Purdue University. HL 99-19: Report #4036-2.

Chen, B. and J.E. Braun, 2001. Simple rule-based methods for fault detection and diagnostics applied to packaged air conditioners, *ASHRAE Trans.*, vol.107, part 1.

Katipamula, S. and S. Gaines. 2003. *Characterization of Building Controls and Energy Efficiency Options Using Commercial Building Energy Consumption Survey*. PNWD-3247. Pacific Northwest National Laboratory. Richland, Washington.

Li, H. and J.E. Braun, 2003. An improved method for fault detection and diagnosis applied to packaged air conditioners, *ASHRAE Trans.*, vol.109, part 2.

Pietsman, J., V. Bakker. 1996. Application of Black-Box Models to HVAC Systems for Fault Detection, *ASHRAE Transactions*, Vol. 102, pt. 1, pp. 628-640.

Reddy, T.A., 2006. Evaluation and Assessment of Fault Detection and Diagnostic Methods for Centrifugal Chillers- Phase II, Final Report for ASHRAE RP1275, ASHRAE, July.

Stylianou, M. & D. Nikanpour. 1996. Performance Monitoring, Fault Detection, and Diagnosis of Reciprocating Chillers, *ASHRAE Transactions* 102(1): 615-627.

#### **Other Information for Bidders:**

- Task 1 - Bidders should demonstrate their knowledge of laboratory and field testing, including any tools that they might have developed or used for performance monitoring of building systems. Bidders should describe the process by which they intend to develop the laboratory and field test protocol. The protocol development process will be an important factor in the evaluation of proposals.
- Task 2 - Bidders are required to provide the details of the laboratory where they intend to perform the laboratory testing, including the characteristics of the centrifugal chiller, instrumentation currently installed on the chiller and additional sensors that will be installed as part of this project. If the chiller is not under the bidders control, they will need attached a letter of commitment from the owner (or manager) of the laboratory to provide the laboratory for testing. Bidders should also provide preliminary estimates of the length of testing period and how the tests will be conducted.
- Task 3 - Bidders are required to provide the details of the field test site(s) where they intend to perform field testing, including the characteristics of all three centrifugal chiller, instrumentation currently installed on the chillers and additional instrumentation that will be installed as part of this project. If the chillers are not under the bidders control, they

will need attached a letter of commitment from the building owner (or manager) clearly indicating the availability of the chillers for testing as part of this research project. Bidders should also provide preliminary estimates of the length of testing period and how the tests will be conducted.

- Task 2 and 3 - Bidders should describe how the method(s) selected will be implemented for online and real-time testing both in the laboratory and in the field. The details should include any prototype software that they intend to use, the preferred language for generating the prototype software and how they intend to get data in real-time for testing and analyzing the FDD methods.
- Contractors should provide detail description of the chillers that are selected for laboratory and field testing. The information should include: 1) size, 2) whether the chiller has sub-coolers, 3) type of mass flow controls (orifice plate, float valve, other restrictor), 4) if it has surge control and 5) how the capacity is controlled. The preferred size for the chillers should be in the range of 200 to 2,000 tons. The chillers can be either single or variable speed.

#### **Evaluation Criteria:**

The following weighting will be used in the selection of the Contractor:

1. Contractor's understanding of the Work Statement, as revealed in the proposal: 20%
2. Quality of methodology proposed for conducting research: 20%
3. Contractor's capability in terms of facilities: 10%
4. Qualifications of personnel for this project: 20%
5. Student involvement: 5%
6. Probability of contractor's research plan meeting the objectives of the Work Statement: 20%
7. Performance of contractor on prior ASHRAE projects or other energy projects (No penalty for new contractors): 5%

#### **Potential Bidders :**

1. Jim Braun ([jbrown@purdue.edu](mailto:jbrown@purdue.edu)), Purdue University
2. Haorong Li ([haorongli@mail.unomaha.edu](mailto:haorongli@mail.unomaha.edu)), University of Nebraska
3. T. Agami Reddy ([reddyta@drexel.edu](mailto:reddyta@drexel.edu)), Drexel University
4. Wang Shengwei ([beswwang@polyu.edu.hk](mailto:beswwang@polyu.edu.hk)), The Hong Kong Polytechnic University

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