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TO: Jin Wen, Chair TC 7.5, jinwen@drexel.edu
Li Song, Research Subcommittee Chair TC 7.5, lsong@ou.edu
Heejin Cho, Work Statement Author(s),

FROM: Michael Vaughn, Manager of Research and Technical Services (MORTS)

CC: William Murphy, Research Liaison 7.0, william.murphy@uky.edu

DATE: July 16, 2019

SUBJECT: Work Statement (1812-WS), "Detection and Diagnosis of Circulating Fluid Leakage from Hydronic Systems"

During their annual meeting, the Research Administration Committee (RAC) reviewed the subject Work Statement (WS) and voted to return with comments.

Below are the issues, concerns, and questions that must be addressed in your next submission of the WS if you choose to resubmit.

1. Provide a cost breakdown.
2. Perhaps a co-sponsor ship with TC 6.1, Hydronic and Steam Equipment and System.
3. Clarify the FDD work.

Please coordinate changes to this Work Statement with your Research Liaison, William Murphy, RL7@ashrae.net or william.murphy@uky.edu prior to resubmitting it to the Manager of Research and Technical Services for further consideration by RAC.

Also, it is necessary that you provide a new TC vote on the revised Work Statement, and a letter describing how each of the above items were addressed in the revision.

If you wish for this work statement to be reconsidered at the next RAC meeting, the revised Work Statement must be sent (electronically) to Michael Vaughn, Manager of Research and Technical Services (morts@ashrae.net) by **August 15, 2019**. The next opportunity for consideration after this deadline is **December 15, 2019** or consideration at RAC's 2020 winter meeting.

Project ID	**1812**	
Project Title	**Detection and Diagnosis of Circulating Fluid Leakage from Hydronic Systems**	
Sponsoring TC	TC 7.5, Smart Buildings	
Cost / Duration	$200,000 / 24 Months	
Submission History	**1st WS Submission, RTAR Accepted F16**	
Classification: Research or Technology Transfer	Basic/Applied Research	
RAC 2019 Annual Meeting Review	**COMPLETE RTAR CHECK LIST CRITERIA BELOW IF RTAR STAGE WAS SKIPPED BY TC**	
RTAR Check List Criteria	**Voted NO**	**Comments & Suggestions**
State-of-the-Art (Background): 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. **RTAR Review Criterion**		
Advancement to the State-of-the-Art 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. **RTAR Review Criterion**		
Relevance and Benefits to ASHRAE: 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. **RTAR Review Criterion**		
IF THE THREE CRITERIA ABOVE ARE NOT ALL SATISFIED - MARK "REJECT" BELOW BUT ADDRESS THE FOLLOWING CRITERIA AS APPROPRIATE		
	RTAR STAGE FOLLOWED	
WS Check List Criteria - START HERE		**Comments & Suggestions**
Detailed Bidders List Provided? The contact information in the bidder list should be complete so that each potential bidder can be contacted without difficulty.		**#9 -** Requires at least three bidders other than WS authors. Only two are provided.
Proposed Project Description Correct? 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.		**#6 -** Correct spelling "manufacturers" : Identify the key stakeholders who will provide input, including industry professionals (e.g. service technicians, installers, consultants, designers), academics/researchers, manufactures, and others; Is there analogies from other industries (such as medical etc.) that could allow a technique such as "catheterization" to measure flow and pressure? Is there techniques used by plumbing such as a pressure test for 24 hrs. that would loose press in an off line, non operational state?
Task Breakdown Reasonable? 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.		**#9** - I have serious concern that FDD is attempted to be used for something that is not amenable to FDD strengths. FDD for air source equipment is usually associated with smoothly varying changes in performance due to changes in inputs, such as pressure or temperature increases as air flow is reduced. Hydronic system performance, especially associated with slow leaks, will exhibit a sudden large change in performance (pump failure or cavitation) once water level or pressure reaches some critical level. There is no advance warning of impending failures due to gradual changes in system performance, or if there may be some subtle change, it is not significant enough compared to the noise from variations in all the system variables. The leakage levels that are of concern are a tiny order of magnitude relative to the main flow rate as to be unmeasurable.
Adequate Intermediate Deliverables? 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.		
Proposed Project Doable? 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.		**#9** - The required data would have to be so precise and the system performance calculations so detailed that FDD methods applied to a complex hydronic system may not be capable of advance warning of minor system leaks.
Time and Cost Estimate Reasonable? 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.		**#6** - I would like a further breakdown of the $200K cost. How was this number arrived at?
Proposed Project Biddable? 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.		**#9** - I fear that prospective proposers will think they will be set up for failure if they respond to this RFP since Task 4 may be unable to produce any useful results. This project is based on there being useful measurements that can identify very slow system leaks. How will this differ from the makeup water systems now currently in use that simply measure water pressure or water level? You suggest that this might even identify the location of a leak, but likely not from gross system performance measurements.
Decision Options	**Initial Decision**	**Suggested Approval Conditions**
ACCEPT		
COND. ACCEPT		**#9** - I fail to see how the data measurements being proposed will be able to identify and locate very slow leaks in inaccessible hydronic piping such as GSHP boreholes or district piping systems. The gradual changes in performance (upon which FDD is based) associated with flow variations in air source equipment operation will not be similar to what is experienced with slow leaks in hydronic systems. **#6 -** Wouldn't there be value having cosponsor ship with TC 6.1 Hydronic and Steam Equipment and System -- it seem that the domain knowledge of practical applications and the value of certain situations where the leaks are more important in certain situations would be a gap in the TC 7.5 group and could be filled in with TC 6.1 team. I would like to see further FDD work clarified; I would like to see a breakdown on the $200kCost.
RETURN	X	
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: 3/14/2019

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

A. Title	x
B Executive Summary	x
C. Applicability to ASHRAE Research Strategic Plan	x
D. Application of the Results	x
E. State-of-the-Art (background)	x
F. Advancement to State-of-the-Art	x
G. Justification and Value to ASHRAE	x
H. Objective	x
I. Scope	x
J. Deliverables/Where Results will be Published	x
K. Level of Effort	
Project Duration in Months	x
Professional-Months: Principal Investigator	x
Professional-Months: Total	x
Estimated $ Value	x
L Proposal Evaluation Criteria & Weighting Factors	x
M. References	x
N. Other Information to Bidders (Optional)	

Title:

Detection and Diagnosis of Circulating Fluid Leakage from Hydronic Systems

WS# 1812

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

Results of this Project will affect the following Handbook Chapters, Special Publications, etc.:

ASHRAE Handbook Applications - FDD

Responsible TC/TG: TC 7.5

Date of Vote:

For		6
Against	*	0
Abstaining	*	1(chair)
Absent or not returning Ballot	*	
Total Voting Members		8

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

Has RTAR been submitted? Yes

Strategic Plan Theme/Goals

Work Statement Authors: **

Kristin Cetin and Zheng O'Neill

Proposal Evaluation Subcommittee:

Chair: Jin Wen (TC 7.5)

Members:

Jeff Spitler (TC 6.8), Srinivas Katipamula (TC 7.5) and Rich

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

Recommended Bidders (name, address, e-mail, tel. number): **

Zheng O'Neill, Univ. of Alabama, zoneill@eng.ua.edu, (205) 348-6982

Kristen Cetin, Iowa State, kcetin@iastate.edu, 515.294.8180.

Bing Dong, Univ. of Texas-SA, bing.dong@utsa.edu, 2104588189

Jim Braun, Purdue, jbraun@purdue.edu, 765-49-49157

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

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

	Yes	No	How Long (weeks)
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?	X		

* Reasons for negative vote(s) and abstentions

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

WORK STATEMENT# 1812

Title:

Detection and Diagnosis of Circulating Fluid Leakage from Hydronic Systems

Sponsoring TC/TG/MTG/SSPC:

TC 7.5 - Smart Building Systems

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

TC 6.8 - Geothermal Heat Pump Systems

Executive Summary:

This project aims to better characterize the common types and extent of leakage of the circulating fluid of hydronic systems such as Ground Source Heat Pump (GSHP) system, chilled/hot water system, etc., as well as to test the ability of existing fault detection and diagnosis (FDD) methods to detect the presence of these leaks using field and/or laboratory test data. The focus will be on hydronic system where a large portion of the system is not accessible (e.g., chilled water pipes in the ground from the central plant to the building)The results of this work will facilitate better, more cost-effective operation of hydronic systems for buildings.

Applicability to the ASHRAE Research Strategic Plan:

This research directly addresses the concept of sustainability, which is the underlying theme of the ASHRAE Strategic Research Plan. This research also directly addresses two of the goals listed in the ASHRAE Strategic Plan 2010-2018.

GOAL 1 Maximize the actual operational energy performance of buildings and facilities. This project aims to develop leakage detection methods for hydronic systems, which can further maximize energy performance in these systems.

GOAL 2 Progress toward…cost-effective net-zero energy buildings (NZEB). NZEBs must be built upon a base of better demand side management. The leakage detection methods proposed in this project will help hydronic systems to reduce energy consumption through improved performance.

GOAL 7: Support the development of improved HVAC&R components ranging from residential through commercial to provide improved system efficiency, affordability, reliability and safety.

Application of Results:

The results of this project may be appropriate for inclusion in Chapter 61 *Smart Buildings Systems* of the HVAC Application Handbook, in Chapter 39 *Operation and Maintenance Management* of the HVAC Applications Handbook, and in Chapter 34 *Geothermal Energy* of the HVAC Applications Handbook. The cognizant chapter TC's are sponsor (TC 7.5) and co-sponsor (TC 6.8) of this WS.

State-of-the-Art (Background):

Leakage detection exists in oil/gas networks and water distribution networks [1-2]. Compared to the HVAC hydronic system, both oil/gas networks and water distribution networks have a relatively long application history in industry. Therefore, there are significant established leakage detection research and applications in oil/gas and water distribution networks such as the negative pressure wave method [3], the acoustic method [4-5], the magnetic flux method [6], the fiber optic sensor method [7], etc. Most of these methods require a number of sensors to be installed in pipelines, which increases the cost of detection. In addition, some researchers studied leakage detection methods based on fuzzy theory [8] or fuzzy combined with neural network theory [9-10] for water distribution networks, which are more complicated than oil/gas networks.

Piping networks in the HVAC hydronic systems are similar with those in oil/gas networks and water distribution networks, but there are distinguished differences between the HVAC hydronic networks and the other two networks. First, the network topology is different. The oil/gas networks and water distribution networks are both open networks, in which the media begins from a source, passes through pressurized pipelines and arrives at the end users. Then the users consume different amounts of media based on their loads. On the contrary, most of HVAC hydronic networks are closed/or semi-closed networks, in which the conditioned media goes from a source to the end users through supply pipelines and gets back to the source through return pipelines to be conditioned again. The media only transfers the heat from the source to users to meet their loads in a closed loop without media consumption. However, there could be some media (e.g., water, steam) loss during the distribution process. Secondly, the media properties are different. Oil pipelines transport the oil with a high density and viscosity. Compared to oil/gas networks and water distribution networks, it is expected that the HVAC hydronic networks have their own characteristics associated with leakage detection research and practice in terms of the topology, medias and operational mechanisms.

Leakage is the main problem that influences the operational performance of pipelines for all hydronic systems including GSHP system. Hydronic systems are commonly used in HVAC applications to circulate water or other heat-carrying fluids through various HVAC equipment, such as chillers, boilers, heat pumps, cooling towers, fan coils, etc. As an example, GSHP systems use the earth's relatively constant temperature to provide heating, cooling, and in some cases, hot water for buildings. According to the U.S. Environmental Protection Agency (EPA) [11], they are among the most efficient and comfortable heating and cooling technologies currently available. EnergyStar-rated GSHPs are over 45% more energy efficient than standard options [12]. However, the GSHP system efficiency can be significantly reduced due to leakage of the circulating fluid - a water and anti-freeze (glycol) mixture - that acts as the heat exchange medium between the ground and the building [13-14]. This is particularly an issue for the system with multiple boreholes.

Numerous studies exist in the literature on fault detection and diagnostics of HVAC equipment including heat pumps using both physics-based models [15-17] and data-driven methods [18-21]. However, there is little research in the area of leakage detection and diagnostics of the circulating fluid for hydronic systems in buildings. For example, currently practitioners watch for possible leaks by monitoring a GSHP system's pressure. However, these pressure values are also influenced by climate conditions (e.g. outdoor and ground temperatures) caused by expansion and/or contraction at varying rates in both the pipes and fluid. It is thus challenging to determine if changes in pressure are due to a leakage issue or just variation due to the influence of environmental conditions. This pressure information also cannot determine the location of the leakage within a system. Some industry practitioners have installed a make-up water meter that monitors the system and adds additional water to the circulating fluid in the case that leakage occurs. However, this method, while it aids in maintaining the pressure of the system, it dilutes the glycol mix and thus its effectiveness, and does not provide any indication of where the leakage problem is occurring or its level of magnitude.

Advancement to the State-of-the-Art:

GSHP systems have proved to be energy-efficient and environment-friendly technologies. There is substantial research in the area of fault detection and diagnosis (FDD) for heat pumps. However, the cause of leakage issues and the ability to determine if a leak has occurred and where it has occurred for GSHP systems are not yet determined. This includes leakage in ground loop heat exchangers and pipes inside and outside buildings, one of the most common operation issues for GSHP system. These leakage issues are also similarly present in HVAC hydronic systems.

In many cases such systems used in buildings are operated by staff with limited to no knowledge of these systems, thus a methodology to detect and diagnose leaks in these systems would be highly beneficial to many building owners and operators, as well as beneficial to the environment.

Research is needed to address the following questions:

- What is the frequency and magnitude of leakage issues in the hydronic system (e.g. GSHP, chilled water system)?
- What types of systems leaks are prevalent, including where they commonly occur? For the GSHP system, were proper installation and testing procedures of the GSHP system followed, in particular, for the ground loop heat exchanger?
- Can the leaks be associated with particular products, installers, or types of connections or valves?
- How effective are existing fault detection and diagnostics methods at detecting and diagnosing leakage problems in practice (e.g., existing methods for gas/oil and water distribution industry) and which method performs best?

Justification and Value to ASHRAE:

The proposed project will advance the knowledge and understanding of the extent and characterization of leakage of the circulating fluid of the HVAC hydronic system, and the associated detection and diagnostics methods of these systems, through the collection and analysis of field and/or laboratory data, and the evaluation of the use of existing fault detection and diagnostics methods (e.g., existing methods for gas/oil and water distribution industry) for these hydronic pipelines.

This research will provide a major contribution to improving the operation of the hydronic systems (e.g., GSHP system) by evaluating and applying existing leakage detection methods where possible. Leakage detection and diagnosis will enable abnormal situations to be detected and diagnosed quickly, helping reduce energy waste and media (e.g., chilled water and hot water) losses while improving the HVAC system operation efficiency. Finally, this research will contribute to the development of a new market for leakage detection technologies.

Objectives:

The objectives of this study are to:

1) Conduct a survey of a diversity of stakeholders, including but not limited to industry professionals, academics, and manufacturers, to better understand the extent and type of leakage issues in hydronic systems;
2) Collect data on the performance of hydronic systems both with and without leaks from at least 6 sites (2 GSHP system and 4 other hydronic systems);
3) Assess the use of existing methods to detect and diagnose leaks in the circulating fluid of hydronic systems;
4) Evaluate the proposed method with measured data from laboratory and/or field data collected in this project.

Scope/Technical Approach:

This project will be divided into two phases.

Phase 1: *Phase I focuses on the developing a comprehensive understanding and documenting known leakage issues in the circulating fluid of hydronic systems, and includes two tasks. Phase 1 is expected to take approximately 8 months to complete.*

Task 1: Conduct a Comprehensive Literature and Dataset Review

Conduct a comprehensive literature review of hydronic systems circulating fluid leakage issues, as well as on existing applicable FDD methods. A review of existing datasets of hydronic and GSHP system data should also be conducted and summarized.

Interim deliverables: A literature review report, describing the principal available leakage detection and diagnostics approaches and sources, shall be presented to the PMSC within the first 4 months of the contract (the literature will, however, continue to be reviewed throughout the term of the project). After the approval from the PMSC, the contractor can proceed to the next task.

Task 2: Develop and Conduct a Survey of Key Stakeholders to Identify and Document Circulating Fluid Leakage Issues

This task includes three subtasks.

Task 2a: Develop a survey instrument: Design a written and/or phone survey to solicit responses from a diversity of hydronic system (e.g., chilled water/hot water system, water source distributed heat pump system, and GSHP system) stakeholders. The purpose of this survey is to help understand the issue of circulating fluid leakage in water source heat pump and other hydronic systems, including the frequency and magnitude of leakage issues, the known causes for their occurrence, and currently practiced methods of detection and repair.

Task 2b: Identify key stakeholders: Identify the key stakeholders who will provide input, including industry professionals (e.g. service technicians, installers, consultants, designers), academics/researchers, manufactures, and others. These stakeholders should represent stakeholders in a diversity of climate zones, and who service a range of system sizes. These survey results will be reviewed and compiled, then used to drive the research focus of the remainder of the project. The proposal should include a draft list of proposed names and/or affiliations of those the contractor proposes to interview and a justification for the proposed list.

Interim deliverables: During the project execution, a draft of the survey based on Task 2a and a list and justification of the targeted stakeholders based on Task 2b should be submitted to the PMSC for review and approval prior to executing the survey.

Task 2c: Execute survey and summarize results: Conduct the survey using the final survey instrument approved by the PMSC. A minimum of 25 total written/phone interviews should be completed, including approximately 10 interviews related to GSHP and 15 related to other hydronic systems.

Interim deliverables: An interim report describing the survey results shall be submitted to the PMSC for review and approval within 8 months of the start of the project.

Phase II: *Phase II focuses on the collection of performance data for hydronic systems and the evaluation of the effectiveness of the use of FDD methods to determine the presence of a fault in such systems.*

Task 3: Collect Performance Data

This task includes three subtasks, all of which should be completed by the end of month 18 of the project.

Task 3a: Identify the systems to be tested, and proposed setup and data collection methods: Identify at least 2 different GSHP and 4 different hydronic systems that will be used for data collection purposes. Explain the data

collection methodology, including for each system, whether the data will field and/or laboratory data, the data points to be collected and associated accuracies, frequency of data collection, length of data collection, and method of data collection including sensors and/or instruments to be used, and whether or not the data referenced is existing data that has already been collected, or data that will be collected throughout the duration of the project. It should be noted that Task 2 and 3 should occur simultaneously. Lesson learned during the assessment conducted in Task 2 shall be leveraged to enhance the data collection.

To facilitate ease of data collection, it is recommended that a partnership(s) be established with, water source heat pump, GSHP and hydronic industry professional(s) and/or building(s) and/or laboratory test facility utilizing GSHP and hydronic system where data already has been collected through operational systems already in place, or where additional data can be collected.

Interim deliverables: By the end of month 9 of the project, the contractor should submit to the PMSC for review and approval, a list of the proposed systems to be used for testing, including details of their type, configuration, age, location, and size at a minimum and available/existing data, as well as a detailed description of the data collection methodology. A simulation plan should also be submitted to the PMSC if it is anticipated that the contractor may not be able to collect sufficient system data in a "faulty" state (see Task 3b) for one or more systems. This submission should identify a plan for development of fault simulation data from a comprehensive hydronic network model to meet the data collection requirements.

Task 3b: Collect and quality control data: Collect data on at least 2 different GSHP and 4 different hydronic systems' performance. This includes at a minimum, one closed-loop vertical GSHP and one closed-loop horizontal GSHP, as well one chilled water loop and one hot water loop. This performance data can be field and/or laboratory data, and should include data collected in different seasonal variations, and also include periods of time in which no leakage and some leakage occurs (i.e., both faulty and fault free data). It is recommended, but not a mandatory, that laboratory testing be conducted, such that the system can be forced to operate under leaky conditions under known ground truth conditions. For the field data collection, larger rather than smaller systems are preferred for data collection. Justifications should be provided for the selection of data sources for this Task. Data collected should include, but is not limited to, outdoor air temperature, outdoor air relatively humidity, system pressure, loop inlet and outlet temperatures, water flow rate, pump performance, and associated pump energy use, etc. Data can be collected from existing already-collected data sources, or additional data collection can also be conducted. Data should cover at least 2 to 3 months for at least the heating and the cooling seasons. The data sampling interval shall be no longer than 5 minutes. All data should be reviewed and quality controlled. Any deviations from the planned data collection approved by the PMSC should also be documented and justification should be provides as to the reason for such deviation.

Interim deliverables: Provide an interim report to the PMSC with a detailed description of the data set and evaluations of the data quality, along with the data sets within 18 months of the start of the project.

Task 4: Evaluate FDD Methods for Use in Leakage Detection

This task is divided into two subtasks. Note: this task can be started while the team is still collecting data in Task 3.

Task 4a: Identify and justify at least 4 FDD methods to be tested and the evaluation criteria: Identify, based on the results of Task 1, existing FDD methods which can be used to detect and diagnose the occurrence of leakage in the circulating fluid of both GSHP and other hydronic systems. Justification shall be provided for the choice of these methods.

Interim deliverables: Submit a list of the proposed methods and justification for the choice of these methods for use in this Task for review and approval by the PMSC prior to executing Task 4b.

Task 4b: Evaluate the use of the FDD methods to detect and diagnose circulating fluid faults: Utilize the field- and/or laboratory-collected data from Task 3 to assess the ability the approved 4 or more types of existing FDD

methods to detect and diagnose the occurrence of leakage in the circulating fluid of both GSHP and other hydronic systems. Such method shall include the leakage detection for both underground ground loop heat exchangers and pipeline on the ground for the hydronic networks. The contractor shall identify the best method of those tested for leakage detection and diagnosis based on statistically-acceptable methods. If existing methods are not appropriate, contractor must explain clearly why they are not appropriate and provide recommendations for an alternative method(s) to be developed in the future.

Interim deliverables: The contractor shall provide the PMSC a written document that details the assessment activities and identifies the targeted FDD methods, justifies their use, and provides set of evaluation criteria used to determine the best methods and justification as to why these methods are the best. This will be reviewed by PMSC prior to the completion of this Task within 22 months of the start of the project.

Task 5: Final Report
Prepare a written report that explains all procedures and algorithms utilized in the testing, the results, and the conclusions; also include all raw and processed data.

Task 6: Technical Papers
Prepare at least one (and preferably two) technical paper to be published in the ASHRAE literature.

Other Information for Bidders

The bidders shall specify their preliminary ideas for carrying out the work. This should include:

- Leakage detection and diagnosis methods to be considered and evaluated;
- The reason to choose these methods;
- Preliminary ideas and information about field/laboratory data collection (both faulty and fault free data).

Deliverables/Where Results Will Be Published:

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.

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. Unless otherwise specified, six copies of the final report shall be furnished for review by the Society's Project Monitoring Subcommittee Committee (PMSC). Following approval by the PMSC 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 CD-ROM; one in PDF format and one in Microsoft Word.

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 publication. Papers specified as deliverables should be submitted as either Research Papers for HVAC&R Research or Technical Paper(s) for ASHRAE Transactions. Research papers contain generalized results of long-term archival value, whereas technical papers are appropriate for applied research of shorter-term value, ASHRAE Conference papers are not acceptable as deliverables from ASHRAE research projects. The paper(s) shall conform to the instructions posted in "Manuscript Central" for an ASHRAE Transactions Technical or HVAC&R Research papers. The paper title shall contain the research project number (1812-RP) at the end of the title in parentheses, e.g., (1812-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.

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 project is planned to have a 24-month duration with a budget of $200,000.

Proposal Evaluation Criteria:

No.	Proposal Review Criterion	Weighting Factor
1	Contractors understanding of the Work Statement as revealed in the proposal	**15%**
2	Quality of methodology proposed for conducting the research (literature review, survey development and execution, data collection, FDD evaluation)	**30%**
3	Capability of collecting data including both faulty and fault-free operations (through evidence of established partnerships and/or existing laboratory facilities to collect field and/or laboratory data that are able to collect sufficient quality, frequency, and diversity of data	**15%**
4	Qualification of personnel for this project	**20%**
5	Student involvement (including undergraduates, graduate students, or both)	**5%**
6	Probability of the contractors research plan meeting the objectives of the Work Statement (including past ASHRAE projects, if applicable, no penalty for new contractor)	**15%**

Project Milestones:

No.	Major Project Completion Milestone	Deadline Month
1	A literature review report, describing the principal available leakage detection and diagnostics approaches and sources, shall be presented to the PMSC.	4
2	An interim draft report describing the survey results shall be submitted to the PMSC for review and approval.	8
3	Provide an interim report to the PMSC with a detailed description of the selected data set and evaluations of the data quality, along with the data sets.	18

4	The contractor shall provide the PMSC a written document that details the assessment activities and identifies the targeted FDD methods, justifies their use, and provides set of	22
5	A final technical report shall be approved by the PMSC	24

Authors:

Kristen Cetin and Zheng O'Neill

References:

[1] Shantanu Datta, Shibayan Sarkar. A review on different pipeline fault detection methods 2016. *Journal of Loss Prevention in the Process Industries*, 41 (2016) 97-106.

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[13] http://greatercomfort.com/blog/geothermalservice/canmygeothermalsystemstartleaking/ Accessed June 2016

[14] https://www.geoexchange.org/forum/threads/helpleakinghorizontalloopwhatdoido.4280/ Accessed June 2016

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clustering. *Control Engineering Practice*, 14 (2006), pp. 1144–1435.

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[21] B. Cai, Y. Liu, Q. Fan, Y. Zhang, Z.Liu, S. Yu and R. Ji. 2014. Multi-source information fusion based fault diagnosis of ground-source heat pump using Bayesian network, *Applied Energy*, Volume 114, February 2014, Pages 1-9, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2013.09.043.

Other Information for Bidders (Optional):

Feedback to RAC and Suggested Improvements to Work Statement Process

Now that you have completed the work statement process, RAC is interested in getting your feedback and suggestions here on how we can improve the process.

1812-WS "Detection and Diagnosis of Circulating Fluid Leakage for Hydronic Systems"

Response to RAC comments and suggestions

Comment 1: Need more field examples and laboratory examples and then validation on existing leaking systems.

We have increased data collection sites from at least 4 sites to 6 sites. The revised objectives are as follows:

- Collect data on the performance of hydronic systems both with and without leaks from at least 6 sites (2 GSHP system and 4 other hydronic systems);
- Evaluate the proposed method with measured laboratory and/or field data collected as a part of this project.

Comment 2: The cover sheet shows the TC 6.8 vote to be 9-1-1 with CNV. The coversheet did not explain the negative vote and should be return to be completed before we review this WS.

The member with the negative vote thought that the WS felt that the proposed WS was too focused on ground source heat pumps. As a result of this comment, we have extended the scope to cover other hydronic system, which include chilled water/hot water systems, water source distributed heat pump systems, etc.

Comment 3: Task 3b is not well defined. What data is to be collected? Are systems going to be forced into a leak condition?

Data collected should include, but is not limited to, outdoor air temperature, outdoor air relatively humidity, system pressure, loop inlet and outlet temperatures, water flow rate, pump performance, and associated pump energy use, etc.

This performance data can be field and/or laboratory data, and should include data collected in different seasonal variations, and also include periods of time in which no leakage and some leakage occurs (i.e., both faulty and fault-free data). It is recommended, but not a mandatory that a laboratory testing should be conducted, so that the system can be forced to operate under leaky conditions (faulty) at known and measureable ground truth conditions.

Task 3b is revised as follows:

- Task 3b: Collect and quality control data: Collect data on at least 2 different GSHP and 4 different hydronic systems' performance. This includes at a minimum, one closed-loop vertical GSHP and one closed-loop horizontal GSHP, as well one chilled water loop and

one hot water loop. This performance data can be field and/or laboratory data, and should include data collected in different seasonal variations, and also include periods of time in which no leakage and some leakage occurs (i.e., both faulty and fault-free data). It is recommended, but not a mandatory that laboratory testing should be conducted, such that the system can be forced to operate under leaky conditions under known ground truth conditions. For the field data collection, larger rather than smaller systems are preferred for data collection. Justification should be provided for the selection of data sources for this Task. Data collected should include, but is not limited to, outdoor air temperature, outdoor air relatively humidity, system pressure, loop inlet and outlet temperatures, water flow rate, pump performance, and associated pump energy use, etc. Data can be collected from existing already-collected data sources, or additional data collection can also be conducted. Data should cover at least 2 to 3 months for at least the heating and the cooling seasons. The data sampling interval shall be no longer than 5 minutes. All data should be reviewed and quality controlled. Any deviations from the planned data collection approved by the PMSC should also be documented and justification should be provides as to the reason for such deviation.

Comment 4: Focus on GSHPs or inaccessible parts of hydronic system.

Yes. The scope of this research project is more on the hydronic system where a large portion of system is not accessible.

Comment 5: Provide interim deliverables for each technical task.

The interim deliverables for each technical task are now more explicitly stated.

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TO: Richard Hackner, Chair TC 7.5, rich.hackner@gdsassociates.com
Jin Wen, Research Subcommittee Chair TC 7.5, jinwen@drexel.edu
CC: Christopher Wilkins, Research Liaison Section 7.0, chris.wilkins@crbusa.com

FROM: Michael Vaughn, MORTS, mvaughn@ashrae.org

DATE: November 16, 2016

SUBJECT: Research Topic Acceptance Request (1812-RTAR), "Detection and Diagnosis of Leakage for Ground Source Heat Pump Systems (GSHP)"

During their fall meeting, the Research Administration Committee (RAC) reviewed the subject Research Topic Acceptance Request (RTAR) and voted to accept it with comments for further development into a work statement (WS) provided that the key comment(s) and question(s) below are addressed to the satisfaction of your Research Liaison, Christopher Wilkins, chris.wilkins@crbusa.com, or RL7@ashrae.net, in the work statement draft.

1. TC 6.8 should be asked to co-sponsor this project.
2. Both laboratory and field tests are needed. Does this mean only an organization with a GSHP test lab is qualified to bid for this project?
3. What does the FDD model look like, and how can the contractor guarantee to deliver a better and workable model compared to existing models?
4. Technical approach needs clarification with details.
5. Budget and duration need better justification in work statement. Budget seems high.

The work statement draft 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 **August 15, 2018** or it will be dropped from display on the Society's Research Implementation Plan. The next likely submission deadline for a new work statement on this topic is **May 15, 2017** for consideration at RAC's 2017 Annual meeting. The submission deadline after that for work statements is **August 15, 2017** for consideration at the RAC's 2017 fall meeting.

Project ID	**1812**	
Project Title	**Detection and Diagnosis of Leakage for Ground Source Heat Pump Systems (GSHP)**	
Sponsoring TC	TC 7.5, Smart Building Systems Co-sponsored by TC 6.8, Geothermal Heat Pump and Energy Recovery Applications	
Cost / Duration	$220,000 / 24 months	
Submission History	**1st RTAR Submission**	
Classification: Research or Technology Transfer	Basic/Applied Research	
RAC 2016 Fall Meeting Review		
Essential Criteria	**Voted NO**	**Comments & Suggestions**
Background: 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.		**#6** - well described. **#14**- Excellent background and citations to references.
Research Need: Based on the background provided is the need for additional research clearly identified? If not, then the RTAR should be rejected.	**#4**	**#6** - well described **#4** - ASHRAE should not use USD 220k to find out what is the extent of the problem. This should form research need. Otherwise I am fine with the proposal. I would also suggest to add one element which is remediation. The important issue is when one needs to act on the system at which leakage level it must be done. **#14** - Needs are well established.
Relevance and Benefits to ASHRAE: 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.	**#5**	**#6** - The project is important and useful for ASHRAE. **#14** - Good linkage o ASHRAE Strategic Plan. Significant contribution to the Application Handbook. Co-sponsorship from TC6.8 a big plus. **#5** - I'm not entirely convinced that there will be a lot of value added by the specific tasks in this RTAR. I think that the first 2 objectives are useful, but I have reservations on the others. If an FDD method were developed and validated for leak detection in ground loops, what would be the outcome? It is likely that digging up an entire loop to pinpoint and repair a leak would be cost prohibitive when compared to replacing the loop, particularly with vertical installations.
IF ABOVE THREE CRITERION ARE NOT ALL SATISFIED - MARK "REJECT" BELOW & CONTINUE REVIEW BELOW		
Other Criteria	**Voted NO**	**Comments & Suggestions**
Project Objectives: 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.	**#5**	**#6-** it seems ok **#7**- This project involves a lot of work. Some of the objectives seem a bit ambiguous. How extensive will the survey be? Both laboratory and field tests are needed. Does this mean only an organization with a GSHP test lab is qualified to bid for this project? What does the FDD model look like, and why can the contractor guarantee to deliver a better and workable model compared to existing models? **#4** - But see research needs. One other objective should be remediation. #5- This is a good progression, but I think the 3rd and 4th objectives might be a bit of a stretch for the scope of this project
Expected Approach and Budget: 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:	**#9, #4, #14, #1**	**#6**- no problems. **#9** - Co-funding partners? Wouldn't the GSHP industry have a stake in this? Not only from an efficiency and maintenance standpoint, but an environmental stewardship standpoint. They don't need to be polluting the ground water and aquifers with leaks. The biggest cost burden for this research should be on industry. **#1** - Needs better clarification on the survey. Budget is high **#4** - Kind of expensive. **#5** - The budget is reasonable for the tasks outlined, but I believe the scope should be reduced and this would have to be reflected in the budget.
References: Are the references provided?		**#14** - Excellent.
Decision Options	**Initial Decision?**	**Final Approval Conditions**
ACCEPT AS-IS		**#7** - This project involves a lot of work. Some of the objectives seem a bit ambiguous. How extensive will the survey be? Both laboratory and field tests are needed. Does this mean only an organization with a GSHP test lab is qualified to bid for this project? What does the FDD model look like, and why can the contractor guarantee to deliver a better and workable model compared to existing models? **#1** - WS should be approved only after satisfactory response to these items. Technical approach needs clarification with details. Budget is high and needs justification in WS. **#4** - Reduce cost, extend by suggesting when remediation should be undertaken, improve research need. **#14-** Need some discussion to justify funding amount and duration.
ACCEPT W/COMMENTS RPS: 3-0-0CNV RAC: 10-0-0 CNV		
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: August 8th, 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	✔

Title:

Detection and Diagnosis of Leakage for Ground Source Heat Pump Systems (GSHP)

RTAR # 1812

(To be assigned by MORTS)

Results of this Project will affect the following Handbook Chapters, Special Publications, etc.:

• Application Handbook: Chapter 61 – Smart Buildings Systems
• Application Handbook: Chapter 39 - Operation and Maintenance Management
• Application Handbook: Chapter 34 – Geothermal Energy

Research Classification:

Basic/Applied Research	✔
Advanced Concepts	
Technology Transfer	

Responsible Committee: TC7.5 Smart Building Systems

Date of Vote: July 20, 2016 (Chairperson Not Voting)

For		8
Against	*	0
Abstaining	*	0
Absent or not returning Ballot	*	2
Total Voting Members		10

RTAR Authors

Lead:
Kristen Cetin and Zheng O'Neill
Others:

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

TC 6.8 -Geothermal Heat Pump And Energy Recovery Applications
Voted on August 11th:14 (For)-0(Against)-2(Absent)

Expected Work Statement Authors

Lead:
Kristen Cetin and Zheng O'Neill
Others:

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

	Yes	No
Has an electronic copy been furnished to the MORTS?	✔	
Has the Research Liaison reviewed the RTAR?	✔	

* Reasons for negative vote(s) and abstentions

Vacations and not available to respond

RTAR # _____

Title:

Insert proposed project title

Detection and Diagnosis of Leakage for Ground Source Heat Pump Systems (GSHP)

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 aims to develop a fault detection and diagnostics (FDD) method (e.g. data-driven, physics-, rules-based) to detect and diagnose leakage problems in ground source heat pump (GSHP) systems. This will facilitate better, more cost-effective operation of GSHP systems for buildings. This will be conducted and validated using both field- and laboratory-measured data.

Background

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

Ground source heat pump (GSHP) systems use the earth's relatively constant temperature to provide heating, cooling, and in some cases, hot water for buildings. According to the U.S. Environmental Protection Agency (EPA) [1], they are among the most efficient and comfortable heating and cooling technologies currently available. Energy Star-rated GSHPs are over 45% more energy efficient than standard options [2]. However, the GSHP system operation and performance can be significantly affected due to leakage of the fluid circulating through buried tubing– a water and anti-freeze mixture - that acts as the heat exchange medium between the ground and the building [3]. The loss of this fluid can lead to infiltration of contaminants into the system, pump cavitation, and air infiltration. It can also lead to environmental contamination from leakage of the anti-freeze [4-5], which can be toxic, corrosive, and/or flammable. These issues have been found, in part, to be due to improper installation and/or materials and settlement over time causing shearing or pullout of the pipes.

Numerous studies exist in the literature on fault detection and diagnostics of heat pumps using both physics-based models [7-9] and data-driven methods [10-12]. However, there is little research in the area of leakage detection and diagnostics of the circulating fluid for GSHPs. Currently practitioners watch for possible leaks by monitoring a GSHP system's pressure. However, these pressure values are also influenced by climate conditions (e.g., outdoor and ground temperatures) caused by expansion and/or contraction at varying rates in both the pipes and fluid. It is thus challenging to determine if changes in pressure are due to a leakage issue or due to the influence of environmental conditions. This is particularly an issue for large systems that can have lost a significant amount of antifreeze solution before being detected. This pressure information also cannot determine the location of the leakage within a system. Some industry practitioners have installed a make-up water meter that monitors the system and adds additional water to the circulating fluid in the case that leakage occurs. However, this method, while it aids in maintaining the pressure of the system, it dilutes the antifreeze mix, and does not provide any indication of where the leakage problem is occurring or its level of magnitude.

Research Need

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

Ground Source Heat Pump (GSHP) systems have proved to be energy-efficient and environment-friendly technologies. There is substantial research in the area of fault detection and diagnostics (FDD) for heat pumps. However, the cause of antifreeze leakage issues and the ability to determine if a leak has occurred and where it has occurred for GSHP systems are not yet determined. This includes leakage in ground loop heat exchangers and pipes inside and outside buildings, one of the most common operation issues for GSHP system. In many cases GSHP systems used in buildings are operated by staff with limited to no knowledge of these systems, thus a methodology to detect and diagnose leaks in these systems would be highly beneficial to many building owners and operators, as well as beneficial to the environment. Research is needed to address the following questions:

1) What is the frequency and magnitude of circulating fluid leakage issues in GSHP systems? Conversations with practitioners indicated this is an issue [13,14] however, there is a need for a systematic survey to understand this issue at a larger scale.

2) Where do circulating fluid leaks commonly occur? What are the causes of these leaks? Were proper installation and testing procedures of GSHP system followed, in particular, for the ground loop heat exchanger? Can the leaks be associated with particular products, installers, or types of connections or valves?

3) What are the energy and cost impacts associated with the occurrence of leaks?

4) What method is the best to detect and diagnose leakage problems in practice in terms of simplicity and low-cost?

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 study are to:

1. Conduct a survey of GSHP industry professionals and experts to better understand the extent of issues of leakage of the circulating fluid;
2. Collect data on the performance of an existing GSHP system operating with and without circulating fluid leaks.
3. Develop a FDD method (e.g data-driven, physics- and/or rules-based) to detect and diagnose the leaks in GHSP system operation fluid;
4. Validate the proposed method with measured data from laboratory and field tests.

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) ( )

(1) A survey of experts will be conducted to help understand the issue of leakage of the circulating fluid in GSHP systems, including the frequency and magnitude of leakage issues, and the known causes for their occurrence. These survey results will be reviewed and compiled, then used to drive the research focus of the remainder of the project. (2) A partnership should be established with a GSHP expert/service company and a building(s) utilizing a GSHP system where data can be collected.(3) Collect data on GSHP performance. This performance data should include data collected in different seasonal variations, and also include periods of time in which no leakage and some leakage occurs from both field and controlled lab tests. Data collected should include, but is not limited to, outdoor temperature, system pressure, loop temperatures, flow rate, pump performance and use. Data can be collected from existing already-collected data, or additional sensors and data collection can also be conducted. (4) Utilize the field-collected data to

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 proposed will advance the knowledge and understanding of leakage detection and diagnostics in GSHP systems through the collection and analysis of actual field and laboratory data, and thorough the development of a simple and low-cost way to assess the occurrence of faults in these systems.
The outcomes from this research will contribute to following Chapters in ASRHAE Handbooks:
• Application Handbook: Chapter 61 – Smart Buildings Systems
• Application Handbook: Chapter 39 - Operation and Maintenance Management
• Application Handbook: Chapter 34 – Geothermal Energy

It is aligned with ASHRAE Strategic Plans and Initiatives:
• Goal 1: Maximize the actual operational energy performance of buildings and facilities;
• Goal 2: Progress toward Advanced Energy Design Guide (AEDG) and cost-effective net-zero-energy (NZE) buildings;
• Goal 7: Support the development of improved HVAC&R components ranging from residential through commercial to provide improved system efficiency, affordability, reliability and safety.

Anticipated Funding Level and Duration

Funding Amount Range: $ 220K

Duration in Months: 24 months

References

List the key references cited in this RTAR

[1]https://yosemite.epa.gov/opa/admpress.nsf/d985312f6895893b852574ac005f1e40/71e68516b78deb968525768c0056f600!opendocument Accessed June 2016
[2] https://www.energystar.gov/products/heating_cooling/heat_pumps_geothermal Accessed June 2016
[3] https://www.geoexchange.org/forum/threads/helpleakinghorizontalloopwhatdoido.4280/ Accessed June 2016
[4] Commonwealth of Pennsylvania, 2000. Ground Source Heat Pump Manual. Department of Environmental Protection. http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-48360/383-0300-001.pdf
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[8] Kim, Woohyun. 2013. Fault Detection And Diagnosis For Air Conditioners And Heat Pumps Based On Virtual Sensors. Open Access Dissertations. Paper 153. http://docs.lib.purdue.edu/open_access_dissertations/153
[9] Y. Chen and L. Lan. 2009. A fault detection technique for air-source heat pump water chiller/heaters. Energy and Buildings, 41(8), 881-887.
[10] D. Zogg, E. Shafai and H.P. Geering. 2006. Fault diagnosis for heat pumps with parameter identification and clustering. Control Engineering Practice, 14 (2006), pp. 1144–1435.
[11] S. Li, and J. Xu. 2014. Operating data monitor system design of ground source heat pump based on embedded system, Software Engineering and Service Science (ICSESS), 2014 5th IEEE International Conference on, On page(s): 1060 – 1063.
[12] B. Cai, Y. Liu, Q. Fan, Y. Zhang, Z.Liu, S. Yu and R. Ji. 2014. Multi-source information fusion based fault diagnosis of ground-source heat pump using Bayesian network, Applied Energy, Volume 114, February 2014, Pages 1-9, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2013.09.043.
[13] Phone and in-person discussions with Jim Bear, Tri-Country Refrigeration, Director - Iowa Geothermal Society.
[14] Personal communications with Dr. Steve Kavanaugh. Author for ASHRAE published book "Geothermal Heating and Cooling: Design of Ground-Source Heat Pump Systems (GSHP)"

Feedback to RAC and Suggested Improvements to RTAR Process

Now that you have completed the RTAR process, RAC is interested in getting your feedback and suggestions here on how we can improve the process.