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Residential HVAC Fault Data Collection Plan: Refrigerant Undercharge and Overcharge Faults

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1. INTRODUCTION

Heating, ventilation, and air-conditioning (HVAC) systems can develop faults due to poor installation practices or gradual wear and tear, leading to decreased HVAC system's efficiency, compromised thermal comfort, and shortened equipment lifespan (EERE, 2018).

Automated fault detection and diagnosis (AFDD) technologies offer a solution by identifying energy-wasting HVAC faults, such as inadequate indoor airflow and incorrect refrigerant charge, and guiding technicians to enhance system efficiency.

In the realm of residential HVAC, AFDD can be implemented through various fault detection and diagnosis capabilities, sensor configurations, and target applications. These technologies typically fall into three categories: smart diagnostic tools, original equipment manufacturer (OEM)-embedded tools, and add-on tools. Smart diagnostic tools employ temporarily installed sensors to directly measure HVAC system characteristics, while OEM-embedded tools utilize factory-installed sensors to identify faults or assess system performance. However, both these types of AFDD technologies are often only accessible for high-end HVAC equipment or require additional sensor installation by qualified technicians, resulting in high investment costs and limited applicability for low-income residential buildings.

On the other hand, add-on tools rely solely on data from smart thermostats and meters to detect faults by continuously analyzing equipment runtime or energy usage. As smart thermostat and meter costs decrease and their prevalence increases, these tools can be readily deployed in low-income residential buildings. However, they possess limited capabilities as they rely solely on basic trend analysis. Enhancing such tools with advanced machine learning algorithms can significantly improve their effectiveness.

1.1 Goals and Objectives

This data collection plan for residential HVAC faults was implemented as a critical component of the Residential HVAC AFDD project's goals. This project aims to overcome various barriers to implementing AFDD in residential buildings.

The barriers to AFDD implementation in residential contexts are diverse. Firstly, the high costs associated with AFDD technology hinder their widespread adoption. The initial investment required for AFDD technology might be perceived as too expensive compared to the perceived benefits. Moreover, the absence of established test standards creates uncertainty among manufacturers and consumers regarding the performance and reliability of these systems. Market challenges, including limited awareness and availability of AFDD technology, further impede implementation. Finally, technical complexity and integration challenges pose additional obstacles to implementation.

Oak Ridge National Laboratory (ORNL) seeks to address these barriers by developing a residential AFDD model designed to minimize sensor requirements. By optimizing sensor placement and utilizing advanced algorithms, this model aims to decrease the overall cost of implementing AFDD in residential settings. This approach aligns with the overarching goal of making AFDD more accessible to homeowners and HVAC service providers.

Therefore, the primary objective of this project is to create a cost-effective, data-driven residential AFDD algorithm. By leveraging data solely from smart thermostats and meters, the AFDD algorithm aims to detect faults and identify potential causes, offering a valuable tool for enhancing HVAC system performance in residential environments. This objective will be achieved through several key steps:

- Generation of fault and fault-free data.
- Development of fault representation approaches in EnergyPlus.
- Construction of physics-informed machine learning-based AFDD algorithms.
- Training of AFDD algorithms using data exclusively from smart thermostats and meters.

The effectiveness of the model will be demonstrated through field experiments, specifically concentrating on improving energy efficiency and guaranteeing occupant comfort. This report includes the project goal, information about the actual residential test facility, the data collection plan, methods for implementing refrigerant undercharge and overcharge faults, and the field test plan to generate both faulty and fault-free data.

In FY24, the ORNL team has three milestones. Table 1 displays the milestone descriptions and their respective due dates.

Table 1 Milestones and its due date

Milestone Description	Due
Provide an updated memo to the DOE outlining the plan that defines the data to be collected, the method of collection (e.g., sensors), and the frequency of data collection for the test building.	March 31, 2024; Q2
The fault-free and fault dataset includes weather data, indoor building data, and energy consumption data.	June 30, 2024; Q3
Provide an updated memo to the DOE regarding the analysis of field data. The identification of variables that can be easily collected and used for the AFDD algorithm will also be included.	September 30, 2024; Q4

1.2 Refrigerant Undercharge and Overcharge Faults

It is essential to understand and address faults in residential HVAC systems to ensure they perform optimally and efficiently use energy. However, there has been a lack of publicly available data on these faults, making it difficult to develop effective solutions.

In the United States, a majority of households rely on air conditioning systems, including central AC or heat pumps (USEIA, 2023). Faults such as refrigerant undercharging and overcharging can significantly waste energy and reduce cooling capacity. For instance, even a slight undercharge can decrease cooling capacity by nearly 13% and reduce energy efficiency by 7.6%. Similarly, excessive refrigerant can harm system components and decrease efficiency (Kim and Braun, 2010).

Refrigerant charge and airflow faults in newly installed residential air conditioners and air-source heat pumps waste approximately 20.7 TWh of site energy annually and contribute to 9.6 million metric tons of unnecessary CO_2 emissions (Winkler et al., 2020).

Despite being common (Chintala et al., 2021), faults like refrigerant over and undercharges lack available data. Given their importance, it's crucial to collect data and develop effective mitigation strategies. To address this gap, the ORNL team initiated a study focusing on refrigerant undercharge and overcharge faults, known for their significant impact on HVAC system performance.

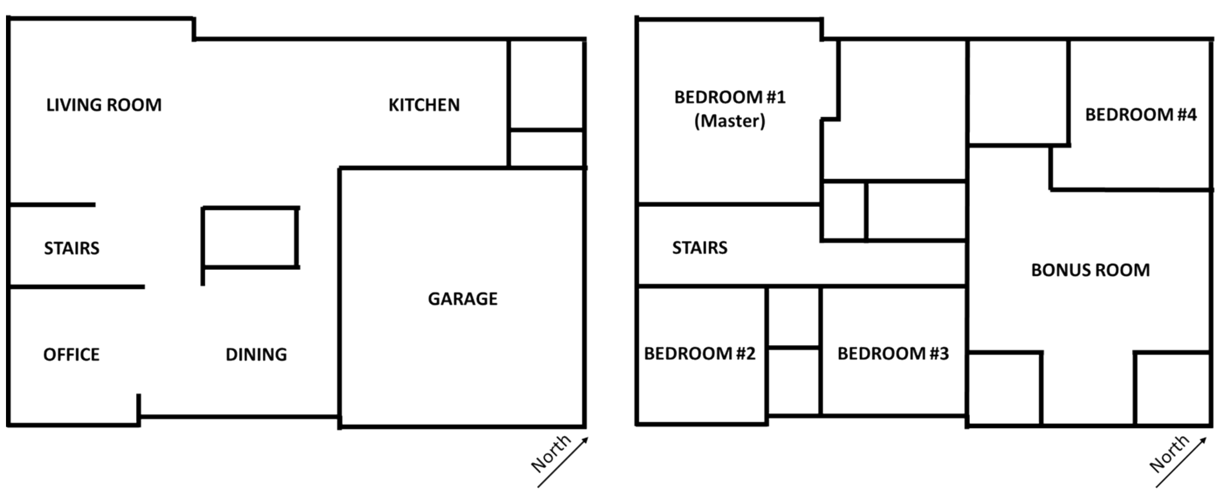
This project aims to generate comprehensive information on refrigerant undercharge and overcharge faults to fill the gap in publicly available fault data. By doing so, it seeks to improve our understanding of HVAC system faults and enhance system performance and energy efficiency on a broader scale.

Furthermore, the gathered data will be used to reduce the number of measuring sensors required for fault detection, thus decreasing the overall implementation cost of AFDD in residential settings.

2. TEST FACILITY

Figure 1 shows the overview of the ORNL's residential test facility. The fault testing and data collection will be conducted at the ORNL's Yarnell Station residence located in Knoxville, Tennessee, within ASHRAE climate zone 4A. Yarnell Station, constructed in 2009, is a two-story single-family detached house with 2,400 ft^2. This building has a slab foundation, and R-13 insulation is used in the upper walls, while R-38 blown-in insulation is used in the attic. During the blower door test, the infiltration rate of the entire house was measured at 2,476 ft^3 per minute (CFM) at 50 Pascals (Niraj et al, 2022). Figure 2 shows the floor plan of the ORNL's residential test facility.

Figure 1. Yarnell Station research house



(a) First floor (b) Second floor

Figure 2. Floor plan of ORNL's residential test facility

Table 2 shows the general information of the ORNL's residential test facility. This test facility is equipped with a 3-ton single-stage heat pump system with a Seasonal Energy Efficiency Ratio (SEER) of 14 for cooling and a Heating Seasonal Performance Factor (HSPF) of 8.2 for heating efficiency. The HVAC system utilizes R-410A refrigerant, which consists of hydrofluorocarbons (HFCs). It is extensively employed in residential air conditioning systems because of its notable efficiency and reduced environmental impact when juxtaposed with older refrigerants such as R-22 (Freon).

Figure 3 shows the installed HVAC system. The installed HVAC system consists of Trane XR 14 Series of outdoor unit (condensing unit) and TEM 6 series of indoor unit (air handler).

Table 2 Yarnell Station information

Conditioned area	2,400 ft^2
Built year	2009
Number of floor	2
Number of bedroom	4
HVAC system	Heat Pump
Stage	1
Size	3 ton
System Efficiency	14 SEER (for cooling)
	8.2 HSPF (for heating)
Refrigerant Type	R-410A

(a) Outdoor unit (TRANE, 2024A)

(b) Indoor unit (TRANE, 2024B)

Figure 3. Installed HVAC system

In the cooling operation of the one-stage air-source heat pump, the system begins by pressurizing the refrigerant gas in the outdoor unit's compressor, which raises its temperature. The hot refrigerant then moves to the outdoor condenser coil, where it transfers heat to the outdoor air, causing it to condense into a liquid. This liquid refrigerant travels to the indoor unit, where it rapidly expands and cools as it passes through an expansion valve or capillary tube. As the cooled refrigerant circulates through the indoor coil, it absorbs heat from the indoor air passing over it, cooling the indoor air. The now-heated refrigerant is cycled back to the outdoor unit, where it's compressed again to restart the cooling cycle.

During the heating operation, the outdoor coil functions as an evaporator, absorbing heat from the outdoor air, causing the refrigerant to evaporate into a gas. The warm refrigerant gas is then pumped to the indoor unit, where a reversing valve directs it to the indoor coil. Inside the indoor coil, the refrigerant releases its heat to the indoor air passing over it, warming the indoor air. The cooled refrigerant returns to the outdoor unit to restart the heating cycle. Throughout both operations, a blower fan inside the indoor unit circulates air over the indoor coil to facilitate heat exchange with the refrigerant and distribute conditioned air throughout the building. Additionally, a thermostat monitors indoor temperature and controls the heat pump's operation to maintain desired comfort levels.

2.1 Refrigerant over and undercharge fault test scenario

Test scenarios were created to evaluate both undercharging and overcharging of refrigerants following consultations with technical experts. Table 3 shows the refrigerant over and undercharge fault test scenarios. For the undercharge tests, five scenarios ranging from -10% to -50% were created, along with one test without faults. Likewise, for overcharge tests, five scenarios from +5% to +25% were established, accompanied by one test without faults.

The cooling season test is scheduled to take place between May and July in the summer of 2024 and the heating season test is planned to occur from December 2024 to February 2025. Each scenario will be conducted over approximately seven days, with possible modifications contingent upon the testing facility's availability. Table 3 and Table 4 show the planned test period for cooling and heating seasons.

During the test, all windows, and exterior and indoor doors will be closed. Shadings will be opened. The heating and cooling setpoint temperature will be set as 68°F and 78°F, respectively (ASRHAE, 2007). There will be no set-back temperature during the nighttime.

- The system's nominal charge is established by measuring its subcooling and adjusting the refrigerant charge according to the manufacturer's charging table.
- For overcharging, add a specific amount of refrigerant to the system as needed. A scale is used to control the amount of added charge each time.
- Conversely, to achieve undercharging, remove a specified amount of refrigerant from the system each time.

Table 3. Refrigerant over and undercharge fault test scenarios

Scenario	Undercharge fault (6)	Overcharge fault (6)

Fault-free	0%	0%
Refrigerant level faults	-10%	+5%
	-20%	+10%
	-30%	+15%
	-40%	+20%
	-50%	+25%

Table 4. Planned test period for cooling season

Test Scenario	Planned Test Period
Baseline 1	May 6, 2024 – May 12, 2024
Undercharge fault: -10%	May 13, 2024 – May 19, 2024
Undercharge fault: -20%	May 20, 2024 – May 26, 2024
Undercharge fault: -30%	May 27, 2024 – June 2, 2024
Undercharge fault: -40%	June 3, 2024 – June 9, 2024
Undercharge fault: -50%	June 10, 2024 – June 16, 2024
Baseline 2	June 17, 2024 – June 23, 2024
Overcharge fault: +5%	June 24, 2024 – June 30, 2024
Overcharge fault: +10%	July 1, 2024 – July 7, 2024
Overcharge fault: +15%	July 8, 2024 – July 14, 2024
Overcharge fault: +20%	July 15, 2024 – July 21, 2024
Overcharge fault: +25%	July 22, 2024 – July 28, 2024

Table 5. Planned test period for heating season

Test Scenario	Planned Test Period
Baseline 1	December 2, 2024 – December 8, 2024
Undercharge fault: -10%	December 9, 2024 – December 15, 2024
Undercharge fault: -20%	December 16, 2024 –December 22, 2024
Undercharge fault: -30%	January 6, 2025 – January 12, 2025

Undercharge fault: -40%	January 13, 2025 – January 19, 2025
Undercharge fault: -50%	January 20, 2025 – January 26, 2025
Baseline 2	January 27, 2025 – February 2, 2025
Overcharge fault: +5%	February 3, 2025 – February 9, 2025
Overcharge fault: +10%	February 10, 2025 – February 16, 2025
Overcharge fault: +15%	February 17, 2025 – February 23, 2025
Overcharge fault: +20%	February 24, 2025 – March 2, 2025
Overcharge fault: +25%	March 3, 2025 – March 9, 2025

3. TEST DATA POINTS & DATA COLLECTION

The ORNL team will collect data at both 1-minute and 1-hour resolutions for all scenarios. During the test, the ORNL team will gather weather-related data including outdoor air temperature and outdoor air relative humidity. The ORNL team will also collect building indoor data, such as indoor air temperature and indoor air relative humidity, along with system-related data including supply and return air temperature, supply and return air relative humidity, supply air flow rate, energy consumption in each HVAC system component, and system runtime fraction.

Table 6 shows the specific data points that the ORNL team will gather for both the fault and fault-free datasets.

Table 6. Data points summary

Data point	Description	Unit
T_Outside_Avg	Outdoor air temperature	°F
RH_Outside_Avg	Outdoor air relative humidity	%
T_L1_Tstat_Avg	Indoor air temperature – First floor	°F
T_L2_Tstat_Avg	Indoor air temperature – Second floor	°F
RH_L1_Tstat_Avg	Indoor air relative humidity – First floor	%
RH_L2_Tstat_Avg	Indoor air relative humidity – Second floor	%
T_LivingRoom_Avg	Indoor air temperature - Living Room (First floor)	°F
T_DiningRoom_Avg	Indoor air temperature - Dining Room (First floor)	°F
Cooling_W_ODUnit	Cooling energy consumption - Outdoor unit	Watts
Cooling_W_IDUnit	Cooling energy consumption - Indoor unit	Watts
Cooling_W_comp	Cooling energy consumption - Compressor	Watts
Cooling_W_ODfan	Cooling energy consumption - Outdoor fan	Watts
Cooling_W_IDfan	Cooling energy consumption - Indoor fan	Watts
Cooling_W_AuxHeat	Cooling energy consumption – Auxiliary heater	Watts
Cooling_T_return	Return air temperature – Cooling mode	°F
Cooling_T_supply	Supply air temperature – Cooling mode	°F
Cooling_RH_return	Return air relative humidity – Cooling mode	%
Cooling_RH_supply	Supply air relative humidity – Cooling mode	%
Cooling_Runtime	System runtime fraction – Cooling mode	%
Cooling_Airflow	Supply air flow rate – Cooling mode	CFM
Heating_W_ODUnit	Heating energy consumption - Outdoor unit	Watts
Heating_W_IDUnit	Heating energy consumption - Indoor unit	Watts
Heating_W_comp	Heating energy consumption - Compressor	Watts
Heating_W_ODfan	Heating energy consumption - Outdoor fan	Watts
Heating_W_IDfan	Heating energy consumption - Indoor fan	Watts
Heating_W_AuxHeat	Heating energy consumption – Auxiliary heater	Watts
Heating_T_return	Return air temperature – Heating mode	°F
Heating_T_supply	Supply air temperature – Heating mode	°F
Heating_RH_return	Return air relative humidity – Heating mode	%
Heating_RH_supply	Supply air relative humidity – Heating mode	%
Heating_Airflow	Supply air flow rate – Heating mode	CFM
Heating_Runtime	System runtime fraction – Heating mode	%

4. PURCHASED ITEMS

In FY 24 Q2, the ORNL team purchased items for upcoming refrigerant undercharge and overcharge fault test. Here is the list of purchased items this quarter.

- 24 pounds of R410A refrigerant
- Charging scale
- Refrigerant charging manifold gauge set

The ORNL team purchased 24 pounds of R410A refrigerant specifically to simulate the refrigerant overcharge fault. The installed HVAC system currently uses 6 pounds and 10 ounces of refrigerant. Consequently, the 24 pounds of R410A refrigerant are sufficient for implementing refrigerant overcharge fault scenarios during the upcoming cooling season test.

The charging scale is designed to accurately measure the quantity of R410A refrigerant introduced into or extracted from the system. It's equipped with a digital interface for precise readings.

The refrigerant charging manifold gauge set, an indispensable diagnostic instrument, facilitates pressure level monitoring within the HVAC unit, enabling us to add or reduce charge amount for the system during operation, and assess system functionality and pinpoint potential issues effectively.

5. CONCLUSIONS AND FUTURE WORKS

In this quarter, the ORNL team worked closely with the lab space manager of ORNL's residential test facility to schedule heating and cooling season tests. Additionally, the ORNL team collaborated closely with technicians to prepare the field tests and to understand the current status of dataloggers and HVAC systems. Consequently, the ORNL team developed test plans for both the summer and winter seasons, as well as purchasing necessary items for the refrigerant undercharge and overcharge fault tests. Field tests will start with the cooling season test in FY24 Q3. During FY24 Q3, the ORNL team will conduct field tests and prepare fault-free and fault datasets.

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