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# Residential HVAC Fault Detection: Field Data Analysis and Interviews with Smart Thermostat Manufacturers


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OAK RIDGE National Laboratory

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Buildings and Transportation Science Division

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## EXECUTIVE SUMMARY

This report presents an analysis of cooling-season field data evaluating how refrigerant undercharge and overcharge faults affect building indoor conditions and HVAC system operation. The report also includes feedback from interviews with six representatives from four smart-thermostat manufacturers.

The FY 2024 Q4 project milestone was to assess the impact of refrigerant faults on indoor conditions and HVAC system operation. Key actions taken include the following:

- Cooling-season test completion
  - Twelve test scenarios were completed: five for refrigerant undercharge faults, five for overcharge faults, and two baseline tests.
- Cooling-season data analysis
  - Refrigerant undercharge faults
    - Low-intensity refrigerant undercharge faults are difficult to detect using only indoor air temperature data.
      - Unmet hours, during which the indoor air temperature exceeds the cooling set point, were observed during 40% and 50% refrigerant undercharge faults. This indicates that the system failed to maintain the desired indoor temperature because of the undercharge.
    - Supply-air temperature increased as the refrigerant undercharge increased.
    - System runtime fraction increased as the refrigerant undercharge increased.
    - Compressor energy consumption decreased as the refrigerant undercharge increased.
  - Refrigerant overcharge faults
    - Refrigerant undercharge faults are hard to detect using indoor air temperature data.
      - In all scenarios, the indoor air temperature was between the cooling and heating set-point temperatures.
    - Refrigerant overcharge faults are hard to detect using supply-air temperature and system runtime fraction.
      - No significant differences were observed in supply-air temperature or system runtime fraction based on the level of the refrigerant overcharge fault.
    - Compressor energy consumption decreased as the refrigerant overcharge increased.
  - Potential variables to detect refrigerant faults
    - Supply-air temperature, system runtime fraction, and compressor energy consumption are potential key variables for detecting refrigerant faults.
    - However, because this was the first round of cooling-season tests, the Oak Ridge National Laboratory (ORNL) team will finalize the initial selection of key variables for refrigerant fault detection after completing the heating-season tests.
- Interview with smart-thermostat manufacturers
  - The goal of the interviews was to understand the current status of residential HVAC automated fault detection and diagnosis (AFDD) functions in smart thermostats and to get feedback on the team's research direction.
  - The ORNL team contacted 10 representatives from six smart-thermostat and HVAC manufacturers.
  - Five interviews were conducted with six representatives from four manufacturers.
  - All interviewees agreed with ORNL's research direction focus on developing cost-effective AFDD solutions for residential HVAC systems.
  - Suggested useful variables for refrigerant fault detection included energy consumption, indoor air relative humidity, and system runtime fraction.
  - Key barriers identified were high costs and challenges with integrating third-party sensors into existing smart-thermostat systems.

In FY 2025, the ORNL team will conduct tests during the heating season (December to March) and cooling season (June to September) and finalize the initial selection of key variables for detecting refrigerant faults. The ORNL team will also maintain regular communication with interviewees to discuss the progress of project. Additionally, the team will reach out to new representatives from various smart-thermostat companies to gather diverse perspectives on the application of AFDD technology in smart thermostats.

# 1. INTRODUCTION

Heating, ventilation, and air conditioning (HVAC) systems can develop faults because of poor installation practices or gradual wear and tear, decreasing HVAC systems' efficiency, compromising thermal comfort, and shortening the lifespan of the equipment (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 field 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 use temporarily installed sensors to measure HVAC system characteristics directly, whereas OEM-embedded tools use factory-installed sensors to identify faults or assess system performance. However, both these types of AFDD technologies are often accessible only 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 because they rely solely on basic trend analysis. Enhancing these tools with advanced machine-learning algorithms can significantly improve their effectiveness.

## 1.1 GOALS AND OBJECTIVES

A 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 the technology's widespread adoption. The initial investment required for AFDD technology might be perceived as too expensive compared with 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 using 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, making it 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, and emphasis will be placed on improving energy efficiency and guaranteeing occupant comfort. This report includes the project goal, information about the residential test facility, the data collection plan, methods for implementing refrigerant undercharge and overcharge faults, and the field test plan to generate both fault and fault-free data.

In FY 2024, the ORNL team had three milestones. Table 1 describes the milestones and lists their respective due dates.

**Table 1. Milestones and their due dates**

| Milestone description | Due date |
|---|---|
| Provide an updated memo to the US Department of Energy (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 DOE regarding the analysis of field data, and include the identification of variables that can be easily collected and used for the AFDD algorithm. | September 30, 2024; Q4 |

## 1.2 REFRIGERANT UNDERCHARGE AND OVERCHARGE FAULTS

Understanding and addressing faults in residential HVAC systems is essential to ensure the systems perform optimally and efficiently use energy. However, the lack of publicly available data on these faults makes developing effective solutions difficult.

In the United States, most households rely on air conditioning systems, including central air conditioning and 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 MMT of unnecessary $CO_2$ emissions (Winkler et al. 2020).

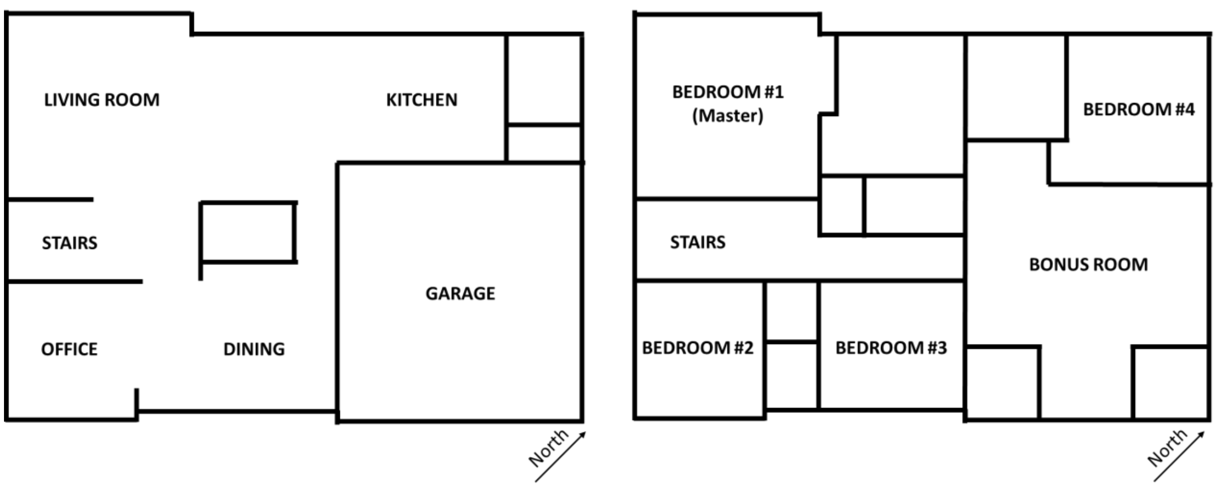
Available data are lacking for faults like refrigerant over- and undercharges, despite these faults being common (Chintala, Winkler, and Jin 2021). Given these faults' significant impact on HVAC system performance, collecting data and developing effective mitigation strategies are crucial. To address this gap, the ORNL team initiated a study focusing on refrigerant undercharge and overcharge faults.

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, the project seeks to improve the 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 ORNL's Yarnell Station residential test facility, which is located in Knoxville, Tennessee, within ASHRAE climate zone 4A. The fault testing and data collection are conducted at this facility. This single-family detached house has a slab foundation, and R-13 insulation is used in the upper walls, whereas 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 $ft^3$/min (CFM) at 50 Pa (Kunwar, Bhandari, and Curcija 2022). Figure 2 shows the floor plan of the ORNL residential test facility. Table 2 shows general information about the ORNL 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. Yarnell Station information**

| | |
|---|---|
| **Conditioned area** | 2,400 $ft^2$ |
| **Built year** | 2009 |
| **Number of floors** | 2 |
| **Number of bedrooms** | 4 |
| **HVAC system** | Heat pump |
| **System stages** | 1 |
| **System size** | 3 ton |
| **System efficiency** | Seasonal energy efficiency ratio of 14 (for cooling) |
| | Heating seasonal performance factor of 8.2 (for heating) |
| **Refrigerant type** | R-410A |

During the cooling operation of the one-stage air-source heat pump, the system begins by pressurizing the refrigerant 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 is compressed again to restart the cooling cycle.

During heating operation, the outdoor coil functions as an evaporator, absorbing heat from the outdoor air and causing the refrigerant to evaporate. 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 the indoor temperature and controls the heat pump's operation to maintain desired comfort levels.

## 2.1 REFRIGERANT OVER- AND UNDERCHARGE FAULT TEST SCENARIO

Following consultations with technical experts, test scenarios were created to evaluate both the undercharging and overcharging of refrigerants. 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 the overcharge tests, five scenarios from +5% to +25% were established, accompanied by one test without faults.

The cooling-season test occurred between May and September 2024, and the heating-season test is planned to occur from December 2024 to February 2025. Each scenario is conducted over approximately 7 days, with possible modifications contingent upon the testing facility's availability. In FY 2024 Q2, the ORNL team provided the planned test period. However, because of weather and facility maintenance, the test period was changed. Table 4 shows the test period for cooling seasons.

**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. Test period for the cooling season**

| Test scenario | Test period |
|---|---|
| Baseline 1 | May 29, 2024–June 5, 2024 |
| Undercharge fault: −10% | June 5–11, 2024, and August 19–26, 2024 |
| Undercharge fault: −20% | June 11–17, 2024, and August 26, 2024–September 3, 2024 |
| Undercharge fault: −30% | June 17–24, 2024 |
| Undercharge fault: −40% | September 3–16, 2024 |
| Undercharge fault: −50% | July 2–8, 2024 |
| Baseline 2 | July 8–15, 2024 |
| Overcharge fault: +5% | July 15–22, 2024 |
| Overcharge fault: +10% | July 22–29, 2024 |
| Overcharge fault: +15% | July 29, 2024–August 5, 2024 |
| Overcharge fault: +20% | August 5–12, 2024 |
| Overcharge fault: +25% | August 12–19, 2024 |

During the test, all windows and both exterior and interior doors were closed. Shading devices were opened. The heating and cooling set-point temperatures were 68°F and 75°F, respectively. There was no setback temperature during the nighttime.

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

## 3. TEST DATA POINTS AND DATA COLLECTION

The ORNL team collected data at both 1 min and 1 h resolutions for all scenarios. During the test, the ORNL team gathered weather-related data including outdoor air temperature and outdoor air relative humidity. The ORNL team also collected 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 5 shows the specific data points that the ORNL team gathered for both the fault and fault-free datasets.

**Table 5. Summary of data points**

| 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 | W |
| Cooling_W_IDUnit | Cooling energy consumption: indoor unit | W |
| Cooling_W_comp | Cooling energy consumption: compressor | W |
| Cooling_W_ODfan | Cooling energy consumption: outdoor fan | W |
| Cooling_W_IDfan | Cooling energy consumption: indoor fan | W |
| Cooling_W_AuxHeat | Cooling energy consumption: auxiliary heater | W |
| 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 | W |
| Heating_W_IDUnit | Heating energy consumption: indoor unit | W |
| Heating_W_comp | Heating energy consumption: compressor | W |
| Heating_W_ODfan | Heating energy consumption: outdoor fan | W |
| Heating_W_IDfan | Heating energy consumption: indoor fan | W |
| Heating_W_AuxHeat | Heating energy consumption: auxiliary heater | W |
| 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. DATA ANALYSIS

In FY 2024 Q4, the ORNL team conducted tests during the cooling season and analyzed the collected data. This chapter presents the results of the cooling-season data analysis, including a detailed examination of data from a representative day.

## 4.1 REFRIGERANT UNDERCHARGE FAULT

To account for the variability in outdoor conditions across different scenarios, the ORNL team began by analyzing the outdoor air temperature. Figure 3 shows the outdoor air temperature trends during the refrigerant undercharge fault tests.

During the baseline test, the maximum outdoor temperature was 100.8°F, and it dropped to 89.3°F during the test for a 10% refrigerant undercharge. The highest minimum outdoor air temperature recorded was 67.4°F during the 50% undercharge fault test, and the lowest was 55.4°F during the 10% undercharge fault test. The highest averaged outdoor air temperature was 82.1°F during the 50% undercharge fault test, and the lowest averaged outdoor air temperature was 72.2°F during the 10% undercharge fault test.

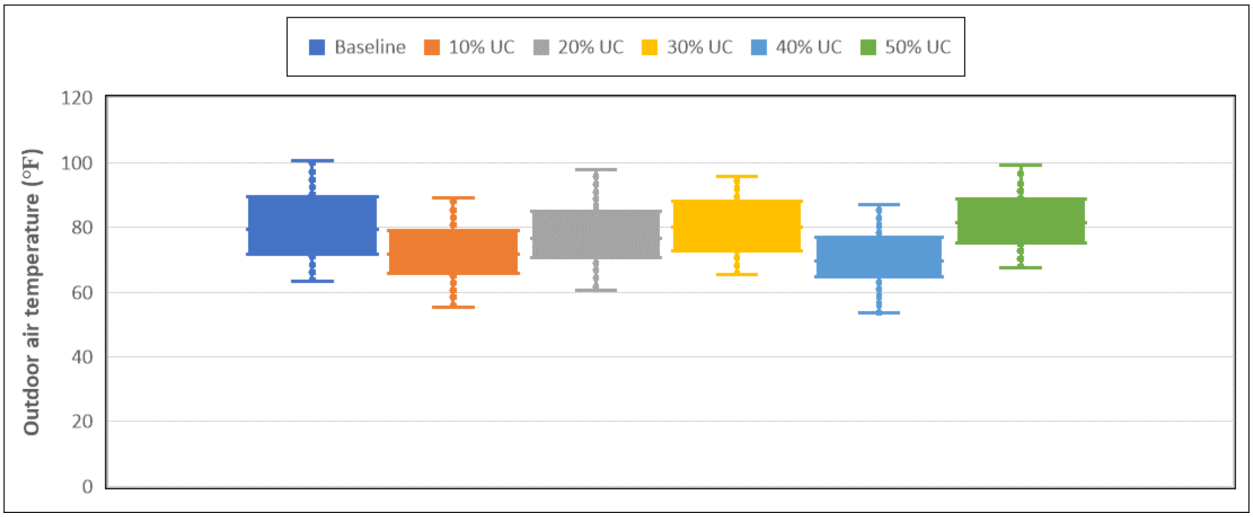
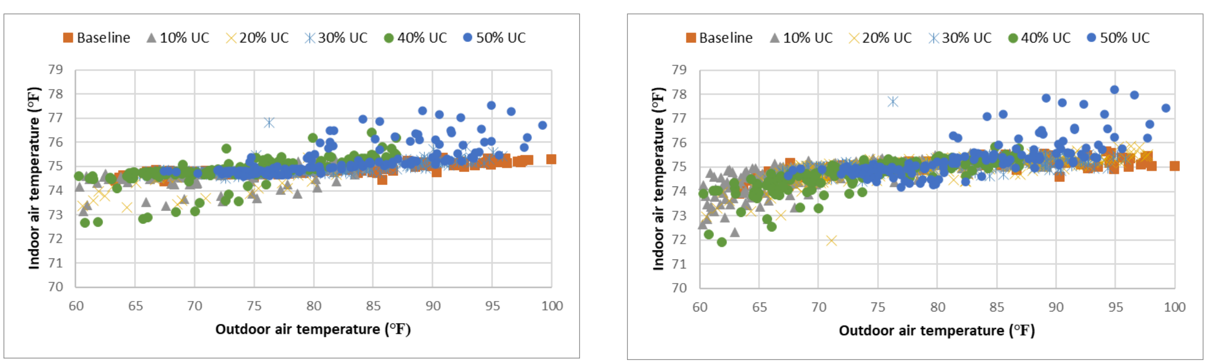



**Figure 3. Outdoor air temperatures during refrigerant undercharge fault tests.**

Figure 4 presents the indoor air temperatures for the first and second floors. As shown in Figure 3, outdoor conditions varied across different test scenarios. Therefore, the ORNL team analyzed the indoor air temperatures in relation to outdoor air temperatures rather than using a time-series comparison.

Until a 30% refrigerant undercharge fault, the indoor air temperatures for both the first and second floors met the cooling set-point temperature (75°F), indicating that the HVAC system provided sufficient cooling for the space. However, starting from a 40% refrigerant undercharge fault, the indoor air temperature exceeded the cooling set-point temperature, meaning the HVAC system could not provide enough cooling because of the refrigerant undercharge fault. This suggests that a refrigerant undercharge fault is difficult to detect using indoor air temperature measurements until the fault reaches 40%.




**(a) First floor** **(b) Second floor**

**Figure 4. Indoor air temperatures for the first and second floors during refrigerant undercharge fault tests.**
UC stands for undercharge.

Figure 5 illustrates the supply-air temperature during tests for refrigerant undercharge faults. In the baseline scenario, the supply-air temperature ranged from 43.9°F to 53.6°F. As the refrigerant undercharge increased, the supply-air temperature also increased. During the 50% refrigerant undercharge test, the temperature ranged from 47.8°F to 58.2°F, which is about 5°F higher than the baseline scenario range. The higher supply-air temperature indicates that the HVAC system could not produce sufficient cold air because of the refrigerant undercharge fault. This directly affected the system's runtime fraction and energy consumption. As shown in Figure 4, with a 50% refrigerant undercharge fault, the indoor air temperature was higher than the cooling set-point temperature, indicating that the HVAC system could not provide enough cooling to the conditioned zone. This means that the 5°F difference in supply-air temperature decreased the effectiveness of space cooling.

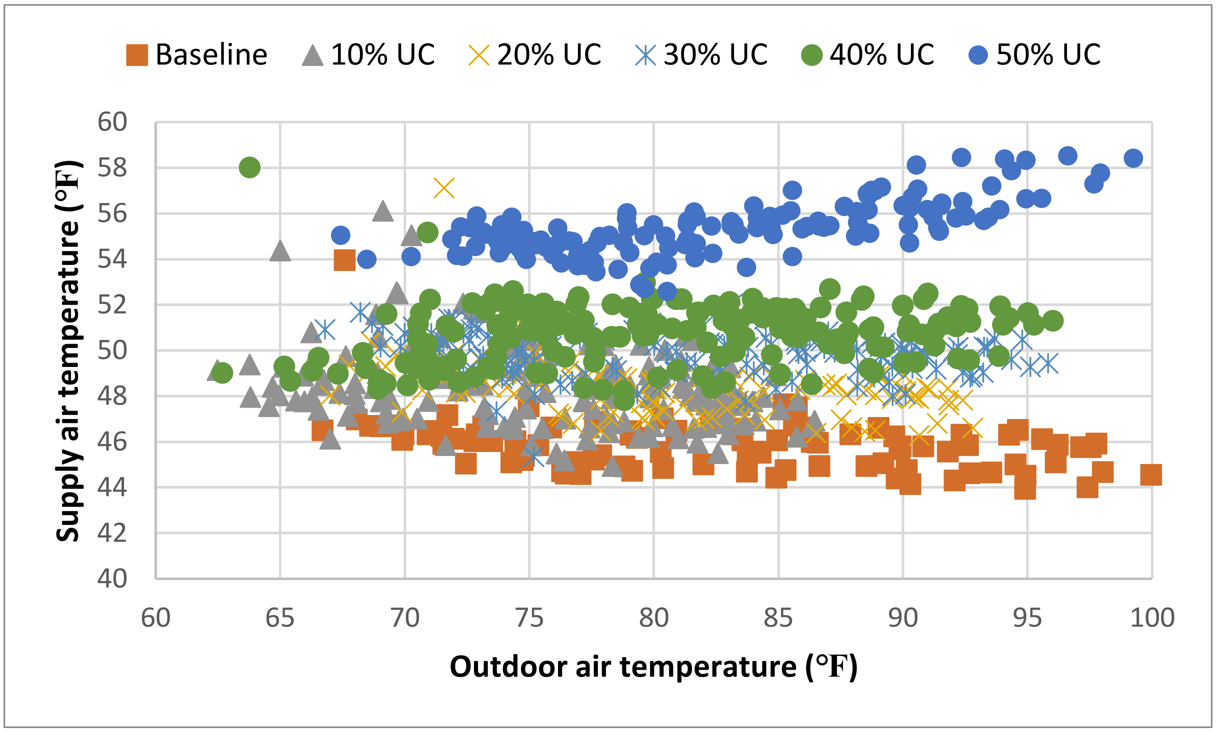



**Figure 5. Supply-air temperatures during refrigerant undercharge fault tests.** UC stands for undercharge.

Figure 6 shows the system runtime fractions with refrigerant undercharge faults. As depicted in Figure 5, as the refrigerant undercharge increased, the supply-air temperature also increased. If the supply-air temperature is higher, then the runtime fraction needs to be larger to provide the same amount of cooling to the conditioned zone. This is why the system runtime fraction during the 50% refrigerant undercharge fault was larger than in the other scenarios.

When the outdoor air temperature was 80°F, the runtime fractions in the other scenarios were around 30%–60%. However, in the case of the 50% refrigerant undercharge fault, the system was fully operated to provide enough cooling. In Figure 4, the indoor air temperature during the 50% refrigerant undercharge fault was higher than the cooling set-point temperature when the outdoor air temperature exceeded 80°F. Back to Figure 6, when the outdoor air temperature was above 80°F, the system was fully operated during the 50% refrigerant undercharge fault. This indicates that when the outdoor air temperature was higher than 80°F, even though the HVAC system was fully operated, it could not provide sufficient cooling to the conditioned zone because of the higher supply-air temperature described in Figure 5.

Through these tests, the ORNL team confirmed that the refrigerant undercharge fault directly affects the supply-air temperature and system runtime fraction, making these potential variables for detecting refrigerant undercharge faults.

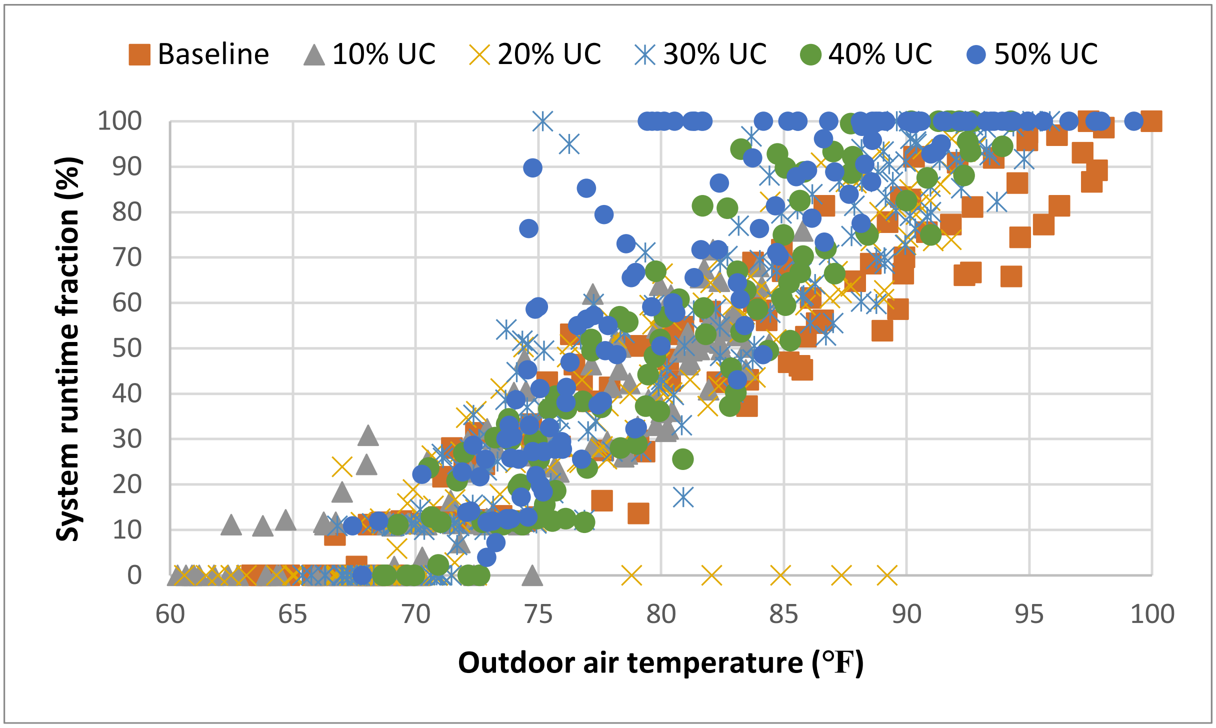
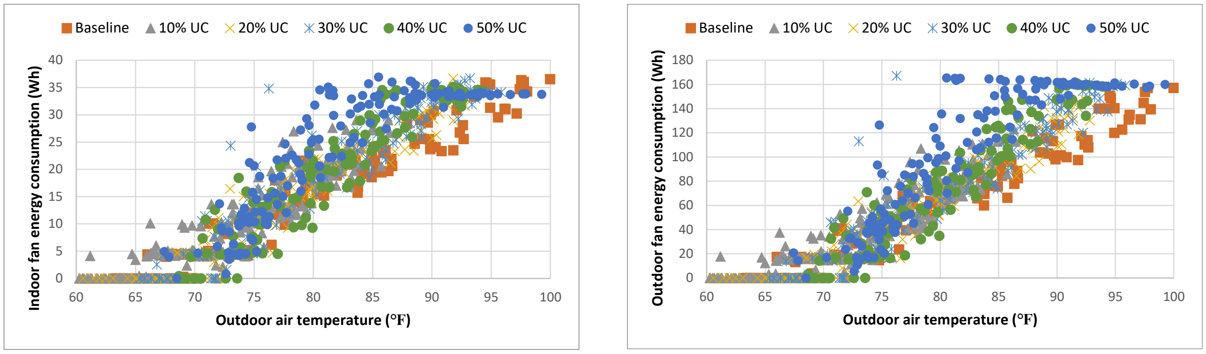



**Figure 6. System runtime fractions during refrigerant undercharge fault tests.** UC stands for undercharge.

Figure 7 displays the energy consumption of the indoor and outdoor fans during tests conducted for refrigerant undercharge faults. The Yarnell Station research house is equipped with a variable air volume fan. However, the system did not operate at two-stage levels because a single-stage operation was sufficient to meet the building's cooling load. The fans were activated when space cooling was required and turned off when the indoor air temperatures on the first and second floors fell between the cooling and heating set-point temperatures. As a result, the energy consumption patterns of the outdoor and indoor fans were quite similar to the system runtime fraction pattern presented in Figure 6.




**(a) Indoor fan** **(b) Outdoor fan**

**Figure 7. Indoor and outdoor fan energy consumption during refrigerant undercharge fault tests.** UC stands for undercharge.

Figure 8 illustrates the compressor energy consumption during the refrigerant undercharge fault tests. The compressor accounted for the largest portion of cooling energy consumption. In contrast to the observed patterns in indoor and outdoor fan energy consumption shown in Figure 7, compressor energy consumption increased with higher outdoor air temperatures. This trend was expected because the cooling load rises when outdoor temperatures are elevated.

The ORNL team anticipated significant differences in compressor energy consumption due to increased system runtime fraction, as shown in Figure 6. However, the differences in compressor energy consumption between the baseline scenario and refrigerant undercharge fault scenarios were not significant.

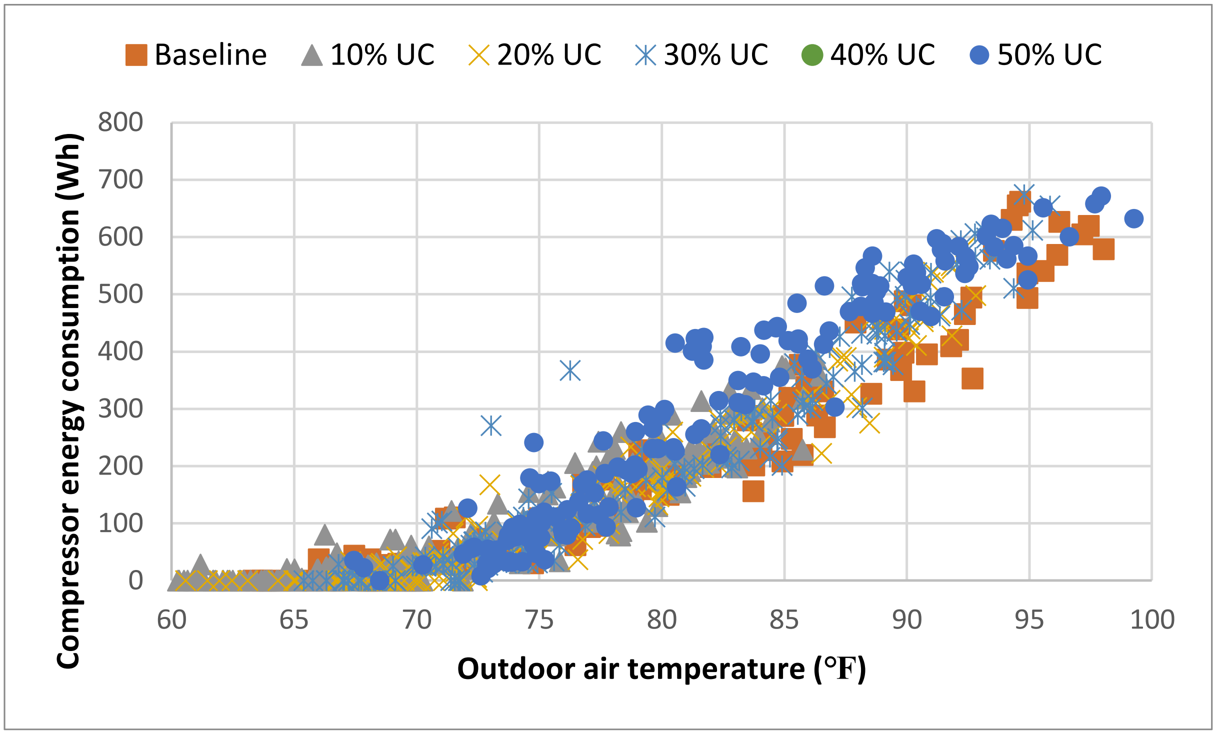



**Figure 8. Compressor energy consumption during refrigerant undercharge fault tests.** UC stands for undercharge.

For a detailed analysis of compressor energy consumption, the ORNL team focused on compressor data when the outdoor air temperature was between 85.0°F and 85.9°F. To remove outliers, the ORNL team focused on selecting data points from 3 minutes after the system was turned on to 3 minutes before the system was turned off. Additionally, any data point where the compressor's energy consumption was less than 300 Wh was considered an outlier and excluded. As shown in Figure 9, the team observed a consistent trend: as the refrigerant undercharge increased, the compressor energy consumption per minute decreased. This decrease in energy consumption is important because it helps explain the pattern of compressor energy consumption observed in Figure 8. Although system runtime fraction increases as refrigerant undercharge fault increases, reduced compressor energy consumption per minute means that the total compressor energy consumption does not necessarily increase.

In summary, although the HVAC system operated more frequently under refrigerant undercharge conditions, compressor energy consumption per minute decreased, and thus no significant increase in hourly compressor energy consumption occurred.

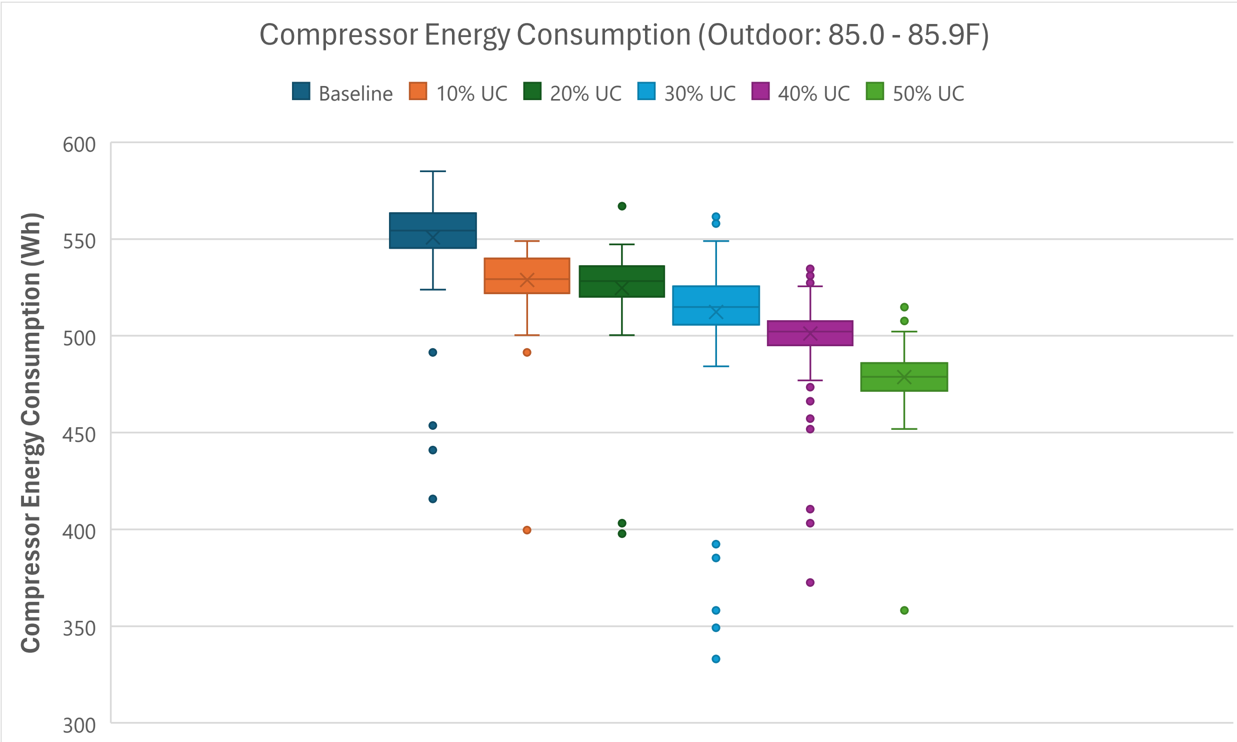



**Figure 9. Compressor energy consumption per minute at outdoor air temperatures between 85.0°F and 85.9°F.**

Also, superheat, the difference between the actual temperature of the refrigerant vapor and its saturation temperature at a given pressure, can explain why compressor energy consumption per minute decreased as refrigerant undercharge fault increased. Figure 10 shows the pattern of superheat during refrigerant undercharge fault tests.

When the refrigerant charge in a system is insufficient (a refrigerant undercharge fault), the evaporation temperature drops below the expected level. This drop leads to an increase in superheat. For example, in the 50% refrigerant undercharge fault scenario, the superheat increased significantly compared with the baseline condition. The superheat levels remained relatively consistent from the baseline scenario to the 30% refrigerant undercharge fault scenario.

From the baseline scenario to the 30% refrigerant undercharge fault scenario, the thermal expansion valve effectively regulated the superheat when the refrigerant charge was adequate. However, when the charge became too low, the mass flow of refrigerant decreased, preventing the thermal expansion valve from maintaining the desired superheat.

From 10% refrigerant undercharge to 30% refrigerant undercharge, the system could still maintain appropriate superheat levels, resulting in good system performance. Within this range, energy consumption was also reduced because of the lower refrigerant mass flow rate, which helped improve overall efficiency.

In summary, with 10%–30% refrigerant undercharge faults, the HVAC system could still effectively achieve the cooling load while exhibiting lower compressor energy consumption. This occurred because the reduced amount of refrigerant meant the compressor did not need to work as hard, reducing energy consumption. Additionally, the lower refrigerant charge decreased the mass flow rate, saving more energy as the system operated. Moreover, slightly higher superheat levels ensured that the refrigerant completely evaporated before returning to the compressor, which protected the compressor from potential damage.

However, when the refrigerant charge was reduced by 50%, the system struggled to meet cooling requirements, although it still consumed less energy. This happened because there was insufficient refrigerant to absorb and transfer the necessary heat load, leading to inadequate cooling performance. Furthermore, the overall capacity of the system was significantly reduced, meaning it could not provide enough cooling regardless of how long it ran.

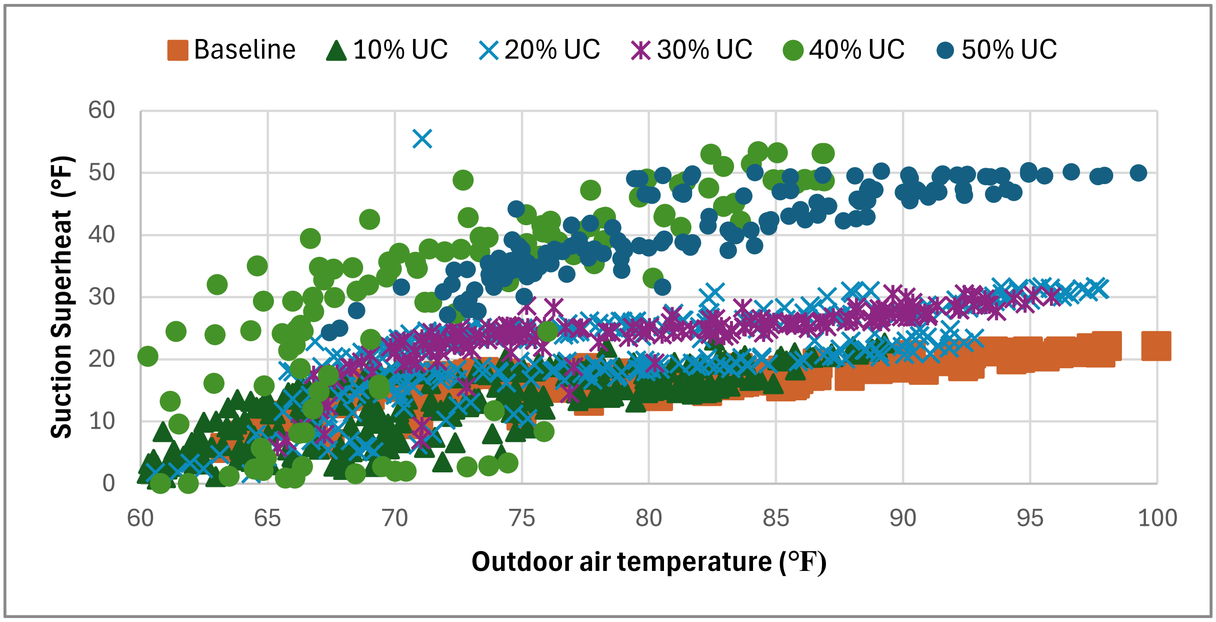



**Figure 10. Superheat during refrigerant undercharge fault tests.** UC stands for undercharge.

## 4.2 REFRIGERANT OVERCHARGE FAULT

Figure 11 shows the outdoor air temperature trends during the refrigerant overcharge fault tests. During the baseline test, the maximum outdoor temperature was 100.7°F, and it dropped to 88.6°F during the 10% refrigerant overcharge test. The highest minimum outdoor air temperature recorded was 69.0°F during the 10% overcharge fault test, and the lowest was 63.3°F during the baseline test. The highest averaged outdoor air temperature was 80.5°F during the baseline test, and the lowest averaged outdoor air temperature was 76.0°F during the 10% overcharge fault test.

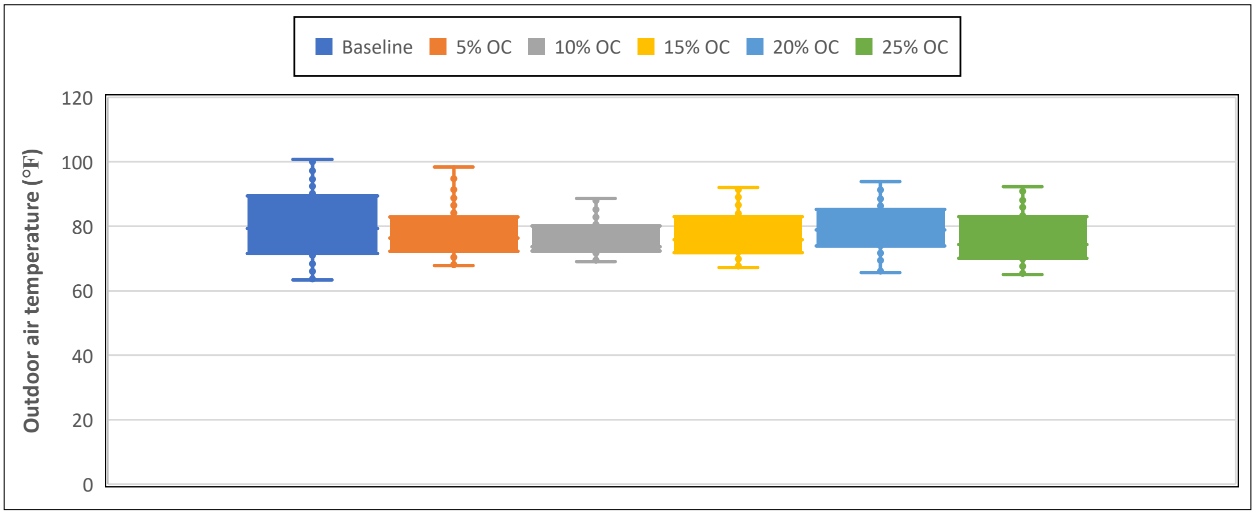
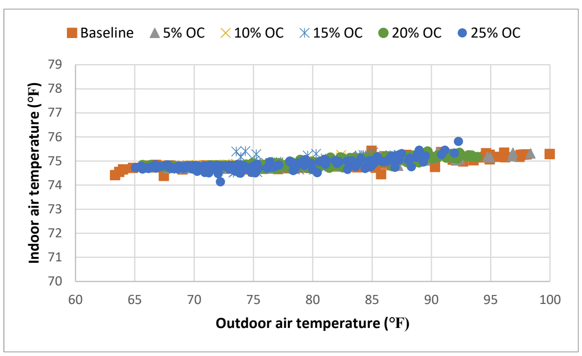
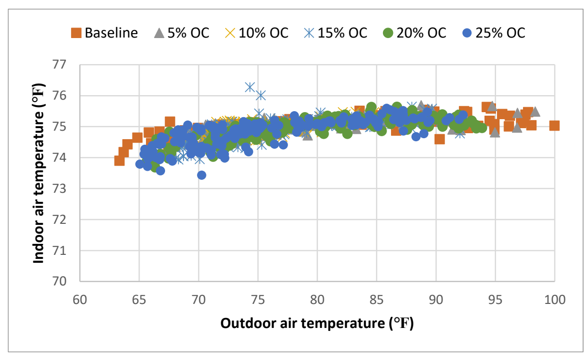



**Figure 11. Outdoor air temperatures during refrigerant undercharge fault tests.** OC stands for overcharge.

Figure 12 displays the indoor air temperatures for both the first and second floors. In contrast to the refrigerant undercharge fault tests, the refrigerant overcharge fault scenarios did not result in unmet hours. The indoor air temperatures on both floors were consistently maintained within the heating and cooling set-point ranges. This indicates that the HVAC system provided sufficient cooling to the conditioned zones regardless of the level of refrigerant overcharge.




**(a) First floor**




**(b) Second floor**

**Figure 12. Indoor air temperatures for the first and second floors during refrigerant overcharge fault tests.** OC stands for overcharge.

Figure 13 shows the supply-air temperatures during the refrigerant overcharge fault tests. In the refrigerant undercharge fault analysis, the supply-air temperature increased by 5°F between the baseline and the 50% refrigerant undercharge fault. However, during the refrigerant overcharge fault tests, no changes in supply-air temperature occurred. For most of the hours, the supply-air temperature remained between 43°F and 48°F regardless of the level of refrigerant overcharge. This indicates that, unlike refrigerant undercharge faults, refrigerant overcharge faults are difficult to detect using supply-air temperature data during the cooling season.

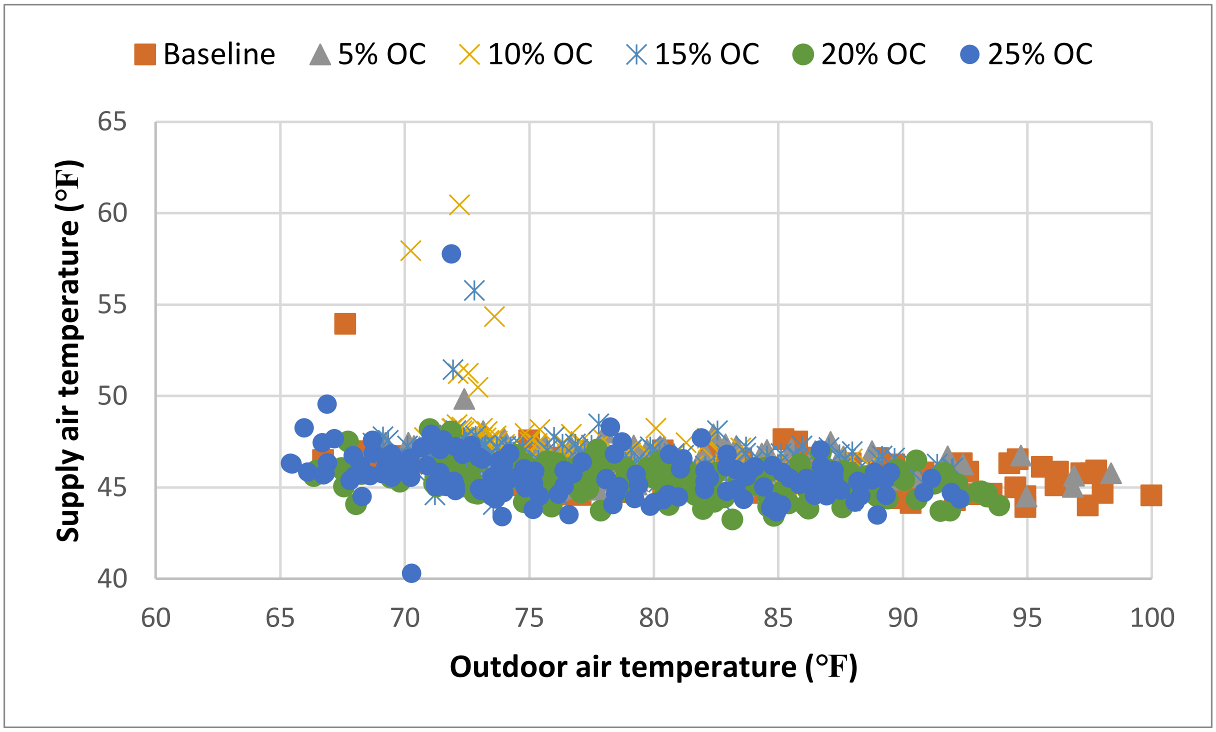



**Figure 13. Supply-air temperatures during refrigerant overcharge fault tests.** OC stands for overcharge.

Figure 14 shows the system runtime fractions during refrigerant overcharge faults. Like with supply-air temperature, differences in runtime fraction are difficult to observe based on the level of refrigerant overcharge. The system runtime fraction increased as outdoor air temperature rose because of the increased building cooling load.

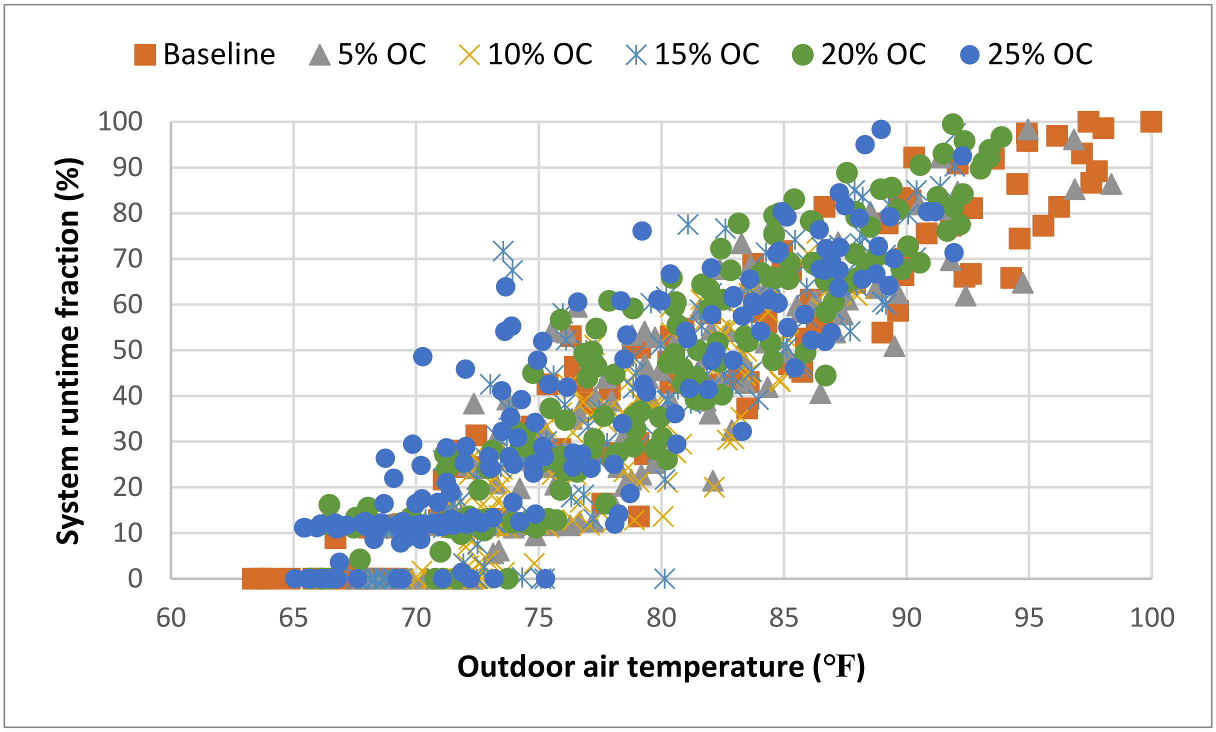
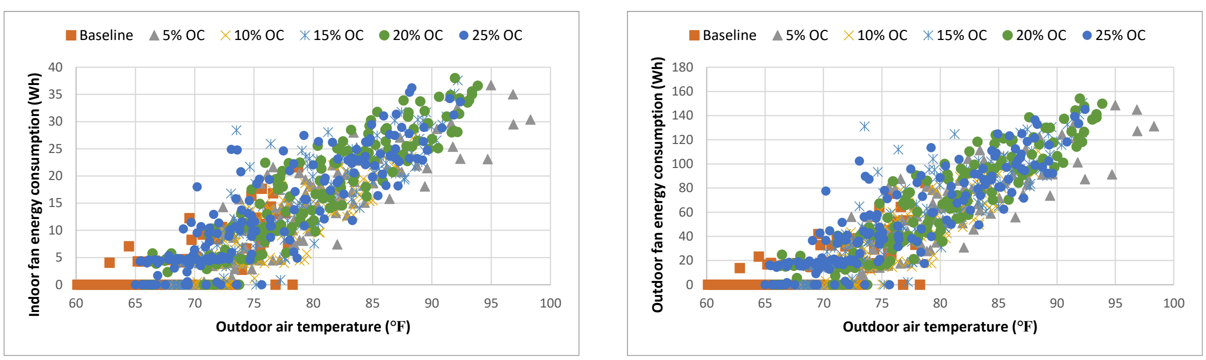



**Figure 14. System runtime fractions during refrigerant overcharge fault tests.** OC stands for overcharge.

Figure 15 illustrates the energy consumption of the indoor and outdoor fans during refrigerant overcharge fault tests. Similar to the observed patterns in indoor and outdoor fan energy consumption during refrigerant undercharge fault tests shown in Figure 7, the energy consumption patterns of both fans align with the system runtime fractions in Figure 14.




**(a) Indoor fan** **(b) Outdoor fan**

**Figure 15. Indoor and outdoor fan energy consumption during refrigerant overcharge fault tests.** OC stands for overcharge.

Figure 16 shows the energy consumption of the compressor during refrigerant overcharge fault tests. Unlike the observed trends in indoor and outdoor fan energy consumption illustrated in Figure 15, compressor energy consumption increased as outdoor air temperature increased. This is a reasonable pattern because cooling load increases with higher outdoor air temperatures. As expected, compressor energy consumption did not align with the runtime fraction pattern. This trend is similar to the compressor energy consumption pattern observed during refrigerant undercharge fault tests and presented in Figure 8. However, while the difference in compressor energy consumption is not significant, it does increase as the refrigerant overcharge increases.

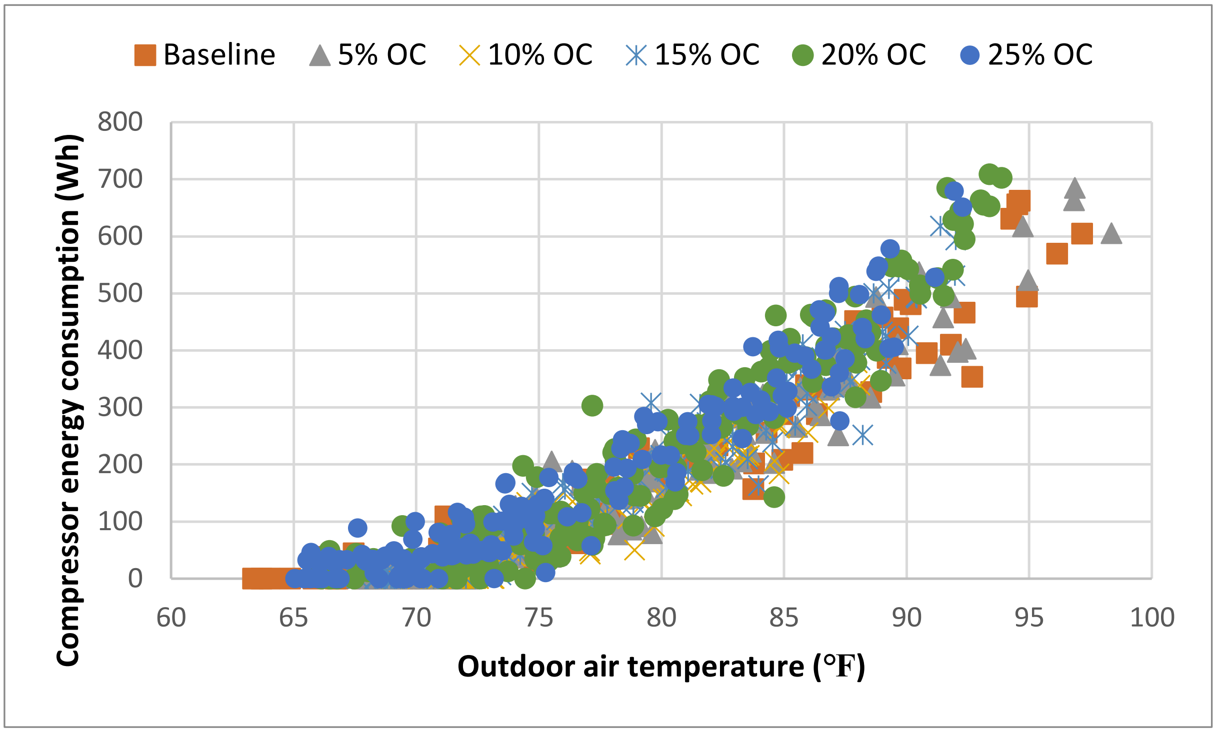



**Figure 16. Compressor energy consumption during refrigerant overcharge fault tests.** OC stands for overcharge.

For a comprehensive analysis of compressor energy consumption, the ORNL team analyzed compressor energy consumption data when the outdoor air temperature ranged from 89.0°F to 89.9°F. "As the ORNL team did for refrigerant undercharge fault analysis, the ORNL team focused on selecting data points from 3 minutes after the system was turned on to 3 minutes before the system was turned off to remove outliers. Additionally, any data point where the compressor's energy consumption was less than 300 Wh was considered an outlier and excluded. Figure 17 illustrates a clear trend: as the refrigerant overcharge increased, compressor energy consumption per minute also increased. This pattern contrasts with the compressor energy consumption observed during refrigerant undercharge faults and depicted in Figure 9.

This increase in energy consumption is significant because it helps clarify the trends in compressor energy consumption shown in Figure 16. Although no notable differences occurred in the system runtime fraction as the refrigerant overcharge level increased, the rise in compressor energy consumption per minute lead to the higher overall compressor energy consumption in Figure 16. This occurred because refrigerant overcharge can increase HVAC system capacity, leading to increased cyclic losses. As a consequence, the compressor energy consumption increases.

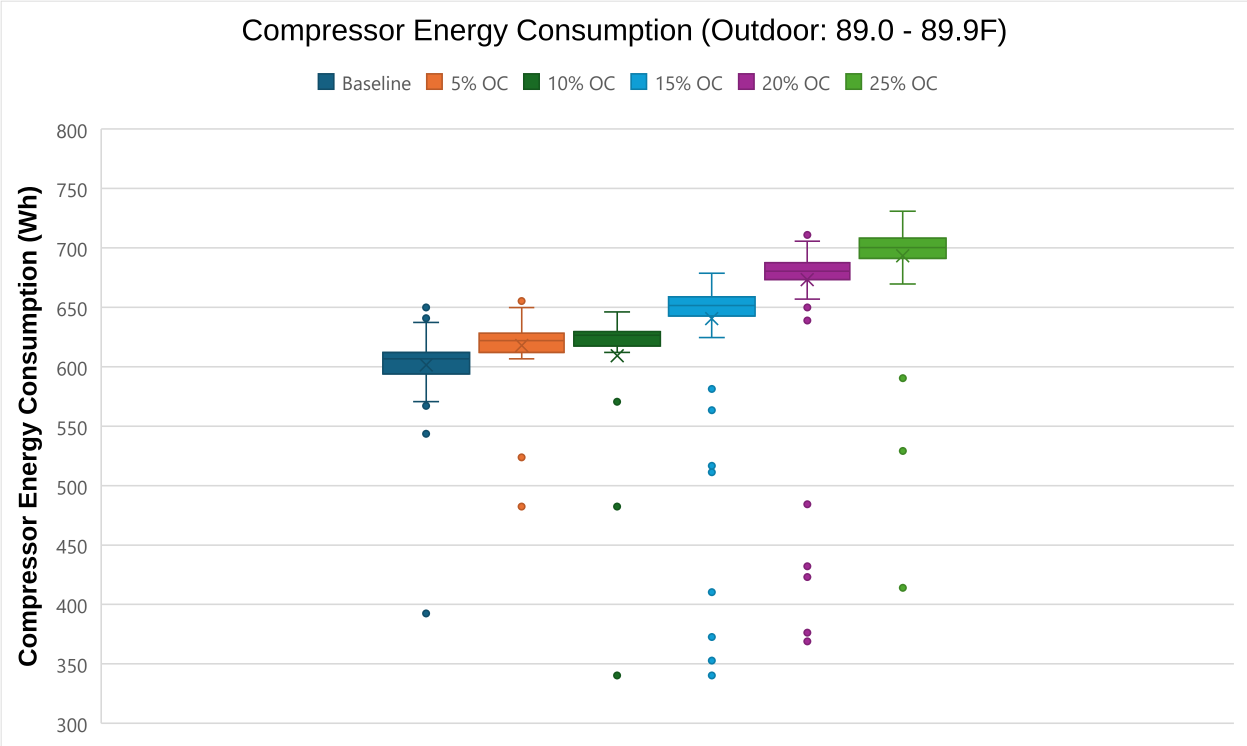



**Figure 17. Compressor energy consumption per minute at outdoor air temperatures between 89.0°F and 89.9°F.**

In summary, refrigerant undercharge and overcharge faults affect HVAC system operation. These faults can reduce system efficiency, resulting in longer runtimes and increased overall energy consumption. Based on the analysis of cooling-season test data, supply-air temperature, system runtime fraction, and compressor energy consumption can be used to detect refrigerant faults during the cooling season.

# 5. INTERVIEW WITH SMART-THERMOSTAT MANUFACTURERS

During FY 2024 Q4, the ORNL team interviewed representatives from smart-thermostat manufacturers. The team contacted nine representatives working in the field of smart thermostats from six different manufacturers. The ORNL team conducted five interviews with six representatives from four smart-thermostat manufacturers.

The purposes of these interviews were as follows:

- To understand the current state of fault detection and diagnostics (FDD) functions in existing residential smart thermostats
- To identify barriers to implementing new FDD features in current residential smart thermostats
- To gather feedback on ORNL's research direction

## 5.1 LIST OF QUESTIONS

The ORNL team asked the following questions related to the current FDD function in smart thermostats and the direction of future development of smart thermostats:

- **Q1**. What should be considered when developing AFDD?
- **Q2**. Which fault can be detected?
- **Q3**. What type of data is used for the fault detection?
- **Q4**. What data can be crucial in improving the accuracy of fault detection?
- **Q5**. Is it possible to connect additional sensors to the existing smart thermostat?

## 5.2 INTERVIEW RESULTS

The interview results are divided into two parts: general comments and responses to the questions listed in Section 5.1. The ORNL team summarized the feedback, which included manufacturers' viewpoints on the project's direction, challenges to implementing residential AFDD technology, and the current status of this technology. The general comments are as follows:

- **Comment 1**: All interviewees agreed with ORNL's research direction, which emphasizes the importance of developing a cost-effective HVAC AFDD strategy for residential buildings.
- **Comment 2**: It is necessary to define representative data points that are both highly correlated with fault detection and cost-effective. Manufacturers noted that achieving high accuracy in AFDD algorithms requires the acquisition of diverse data through measurements. However, installing sensors at every potential measurement point is challenging because it would increase costs, and the relevant data points may vary by manufacturer.
- **Comment 3**: The long payback period is a significant barrier to implementing HVAC AFDD functions in residential buildings. To implement AFDD, additional sensors may need to be installed during the setup of the HVAC system. Moreover, if manufacturers offer AFDD services on a subscription basis, a monthly fee could be added to the maintenance costs of the equipment. To offset these costs, HVAC systems with AFDD must have longer lifespans than systems without it, and the maintenance costs associated with AFDD must be lower than the replacement costs. Therefore, assessing the economic benefits of AFDD in the short term can be very challenging. Additionally, these factors must be convincing to customers.
- **Comment 4**: Current AFDD systems primarily focus on diagnosing equipment failures rather than optimizing energy efficiency. Existing AFDD algorithms developed by manufacturers are mainly focused on detecting equipment malfunctions. Faults that occur during installation, such as refrigerant

overcharge or undercharge, are typically addressed by technicians. However, these types of faults are difficult for occupants to detect, and as a result, they often go unresolved. Over time, this can lead to a continuous decline in energy efficiency.

Responses to the questions varied among the manufacturers. In some cases, detailed information was not allowed to be shared. The following is a summary of the responses to the questions:

- **Response 1-1**: Occupants are likely to ignore or pay little attention to fault alarms. In general, occupants have difficulty identifying faults unless the system has malfunctioned or the occupants have experienced thermal discomfort.
- **Response 1-2**: Balancing precision and recall in fault detection is important to avoid unnecessary alerts. For example, on days when the weather generates a load close to the peak, unlike in usual conditions, the AFDD algorithm might continuously send alerts if the trend or average of the indoor temperature or energy usage deviates from the norm, even if no actual fault exists in the system. Additionally, in typical situations, a slightly overcharged or undercharged refrigerant may not cause a significant change in the indoor environment or energy usage pattern. Therefore, it is essential to establish clear criteria for when the AFDD algorithm should send alerts.
- **Response 1-3**: An appropriate data interval must be determined by considering both the accuracy of the AFDD algorithm and the data-processing capabilities of the smart thermostat. From an algorithmic-accuracy perspective, high-resolution data are beneficial for identifying faults and enable more detailed analysis, providing valuable insights. However, because the data-processing capabilities of smart thermostats are limited, high-resolution data might not be storable or processable by these devices. Therefore, it is essential to define a data interval that offers usable data while ensuring the accuracy of the AFDD algorithm.
- **Response 2**: The types of faults vary depending on the manufacturer. However, in general, issues such as low or high refrigerant pressure, supply-air flow rate, and system breakdowns could be detected through the built-in FDD system.
- **Response 3**: Environmental data such as indoor air temperature, relative humidity, and supply-air flow rate were used. The system data used for fault detection were refrigerant suction/discharge pressure, on/off signals, and runtime fraction.
- **Response 4**: Using outdoor and indoor air temperature data for fault detection provides indirect insights into the cooling or heating load. Comparing the set-point temperature with the indoor air temperature gives information related to system capacity. Supply-air temperature also serves as an indicator of capacity. Indoor humidity contributes data on enthalpy. System runtime and real-time energy consumption data can reveal abnormal HVAC system operation. By integrating these data points, fault detection performance can be enhanced, leading to more accurate diagnostics through comprehensive analysis.
- **Response 5**: Directly connecting third-party sensors to a smart thermostat can be challenging because of protocol compatibility issues. When embedding an AFDD algorithm into a smart thermostat, sensors need to be connected via wired methods, and a compatible protocol is required for data transfer. However, most manufacturers do not make their protocols publicly available, meaning sensors from the same manufacturer are typically required. On the other hand, if sensors are connected wirelessly, using third-party sensors may be possible, but verifying compatibility beforehand is important.

# 6. CONCLUSIONS AND FUTURE WORK

In FY 2024 Q4, the ORNL team successfully completed the first cooling-season test and analyzed field data to assess the impact of varying levels of refrigerant undercharge and overcharge faults on indoor conditions and HVAC system operations.

The team found that using indoor air temperature alone (which does not require additional sensors) makes detecting refrigerant undercharge faults difficult. However, high-intensity refrigerant undercharge faults, such as a 50% undercharge, can be identified. Key indicators for detecting undercharge faults include supply-air temperature, system runtime fraction, and compressor energy consumption. As the refrigerant undercharge increases, the supply-air temperature and system runtime fraction also increase, whereas compressor energy consumption decreases when the outdoor air temperature remains in a similar range.

Detecting refrigerant overcharge faults using only building indoor conditions is challenging. However, compressor energy consumption is a useful indicator because it increases with higher levels of refrigerant overcharge in the same outdoor temperature range.

Overall, supply-air temperature, system runtime fraction, and compressor energy consumption are potential key variables for detecting refrigerant faults. However, this was only the first round of cooling-season tests; the ORNL team will finalize the initial selection of key variables for refrigerant fault detection after completing the heating-season tests.

The ORNL team reached out to 10 representatives from six different smart-thermostat and HVAC manufacturers to understand the current state of residential AFDD technology in smart thermostats as well as the challenges of implementing this technology. They also discussed future research directions. Five interviews were conducted with six representatives from four manufacturers.

All interviewees supported ORNL’s research direction, which highlights the need for a cost-effective HVAC AFDD solution for residential buildings. They suggested that variables such as energy consumption data, indoor air relative humidity, and system runtime fraction could be useful for detecting refrigerant faults. Additionally, they emphasized the importance of alert systems and data-reporting intervals. However, they also identified key barriers to implementing an AFDD algorithm in smart thermostats, such as high costs and the challenge of integrating third-party sensors into existing smart-thermostat systems.

In FY 2025, the ORNL team will conduct heating-season tests and finalize the initial selection of key variables for detecting refrigerant faults. Additionally, the team will maintain ongoing communication with interviewees to discuss research progress. The ORNL team will also reach out to new representatives from other smart-thermostat companies to gain different perspectives on residential AFDD technology in smart thermostats.

# 7. ACKNOWLEDGEMENT

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