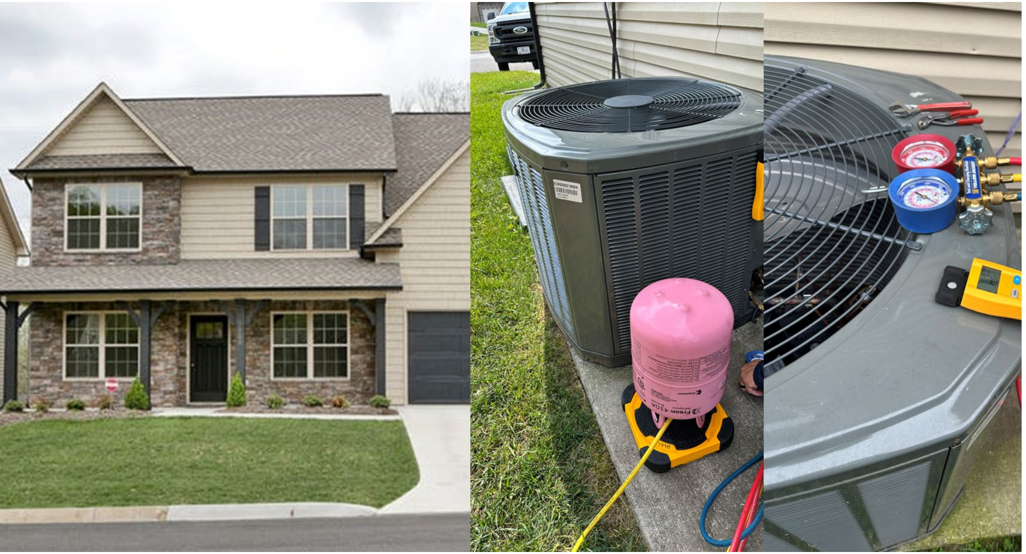
2024 PROJECT PEER REVIEW

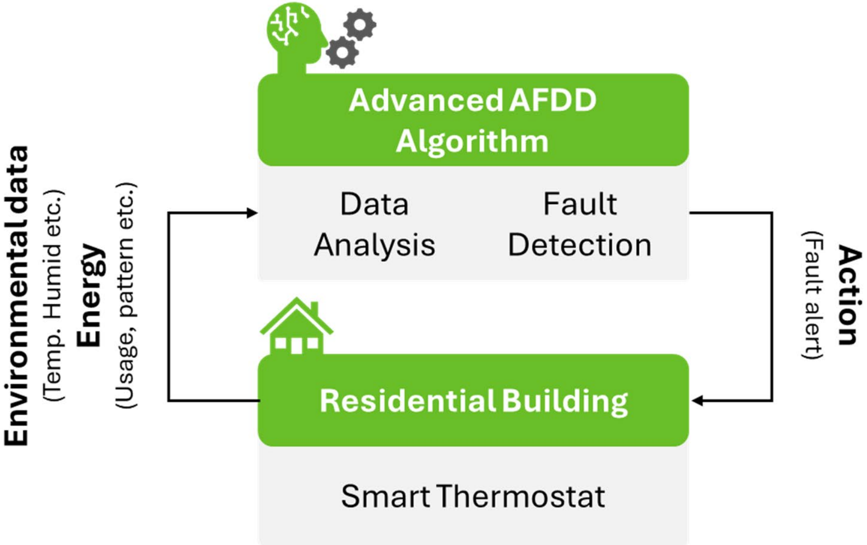
U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review:

Developing and Deploying a Cost-Effective Residential AFDD

Developing and Deploying a Cost-Effective Residential AFDD





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Project Summary

OBJECTIVE, OUTCOME, AND IMPACT

- Develop and evaluate a cost-effective AFDD solution for residential buildings
- Develop AFDD algorithm that can be integrated into smart thermostats
- Generate publicly accessible dataset of refrigerant faults and fault-free refrigerants

TEAM AND PARTNERS

- **Project team:** Piljae Im, Yeobeom Yoon, Islam Safir, Sungkyun Jung, Junjie Luo, Vishaldeep Sharma, and Young Jae Choi
- **Technical Advisory Group:** Manufacturers of smart thermostats and residential HVAC systems

STATS

Performance Period: 10/1/2023–9/30/2026 (TBD)

DOE Budget: $180k, Cost Share: $0k

Milestone 1: Data collection plan

Milestone 2: Generate fault-free and fault data

Milestone 3: Analyze field data and identify variables to collect and use for fault detection

Problem

- HVAC system faults are responsible for wasting 15%–30% of total energy consumption
- Refrigerant charge faults and airflow faults in residential air conditioners and heat pumps contribute to 20.7 TWh of wasted energy annually
  - Equivalent to 9.6 million metric tons of CO_2 emissions
- 60% of previous research focused on HVAC systems in large commercial buildings; only 16% targeted medium and small commercial buildings or residential buildings
- High costs and long payback periods are key barriers to implementing AFDD functions in residential buildings

S. Katipamula, M.R. Brambley, Methods for fault detection, diagnostics, and prognostics for building systems—A review, Part I, HVAC&R Research 11 (2005).
J. Winkler, S. Das, L. Earle, L. Burkett, J. Robertson, D. Roberts, C. Booten, Impact of installation faults in air conditioners and heat pumps in single-family homes on US energy usage, Applied Energy 278 (2020).
W. Kim, S. Katipamula, A review of fault detection and diagnostics methods for building systems, Science and Technology for the Built Environment 1 (2018).
A.P. Rogers, F. Guo, B.P. Rasmussen, A review of fault detection and diagnosis methods for residential air conditioning systems, Building and Environment 161 (2019).

Alignment and Impact

The DOE Decarbonization Blueprint targets a 65% cut in greenhouse gas emissions by 2035 and a 90% reduction by 2050. Achieving these goals necessitates a reduction in energy use intensity for both residential and commercial buildings

Cross-cutting goals

- **Equity**: Propose cost-effective residential AFDD algorithms that promote equity by being suitable for both typical residential buildings and low-income communities
- **Affordability**: Propose affordable sensor suitable for integration with current smart thermostats to detect refrigerant faults

Strategic objectives

- **Energy Efficiency**: Refrigerant fault detection helps avoid system energy inefficiencies. The proposed cost-effective residential HVAC AFDD would increase AFDD technology adoption in residential buildings, including in low-income communities
- **Onsite Emissions Reduction**: Detection of refrigerant faults can reduce wasted energy consumption, resulting in decreased operational emissions

Alignment and Impact

This project aims to minimize AFDD technology implementation costs and overcome long payback period by proposing a cost-effective AFDD algorithm with a minimal number of sensors, suitable for both residential buildings and low-income communities

Project impacts:

- **Cost-effective AFDD algorithm**
  - The project aims to develop a cost-effective AFDD algorithm for residential buildings that uses a minimal number of sensors to reduce implementation costs, overcoming a long payback period (a barrier of existing residential AFDD technology)
- **Integration with smart thermostats**
  - Increasingly affordable smart thermostats and smart meters are now accessible for even low-income residential buildings. Integrating an AFDD algorithm with smart tech could lead to development of a cost-effective AFDD algorithm for residential buildings
- **Publicly accessible dataset**
  - The ORNL team will generate a publicly accessible fault dataset covering both heating and cooling seasons. Given the limited availability of actual building data, this dataset will be valuable for developing, evaluating, and validating an AFDD algorithm

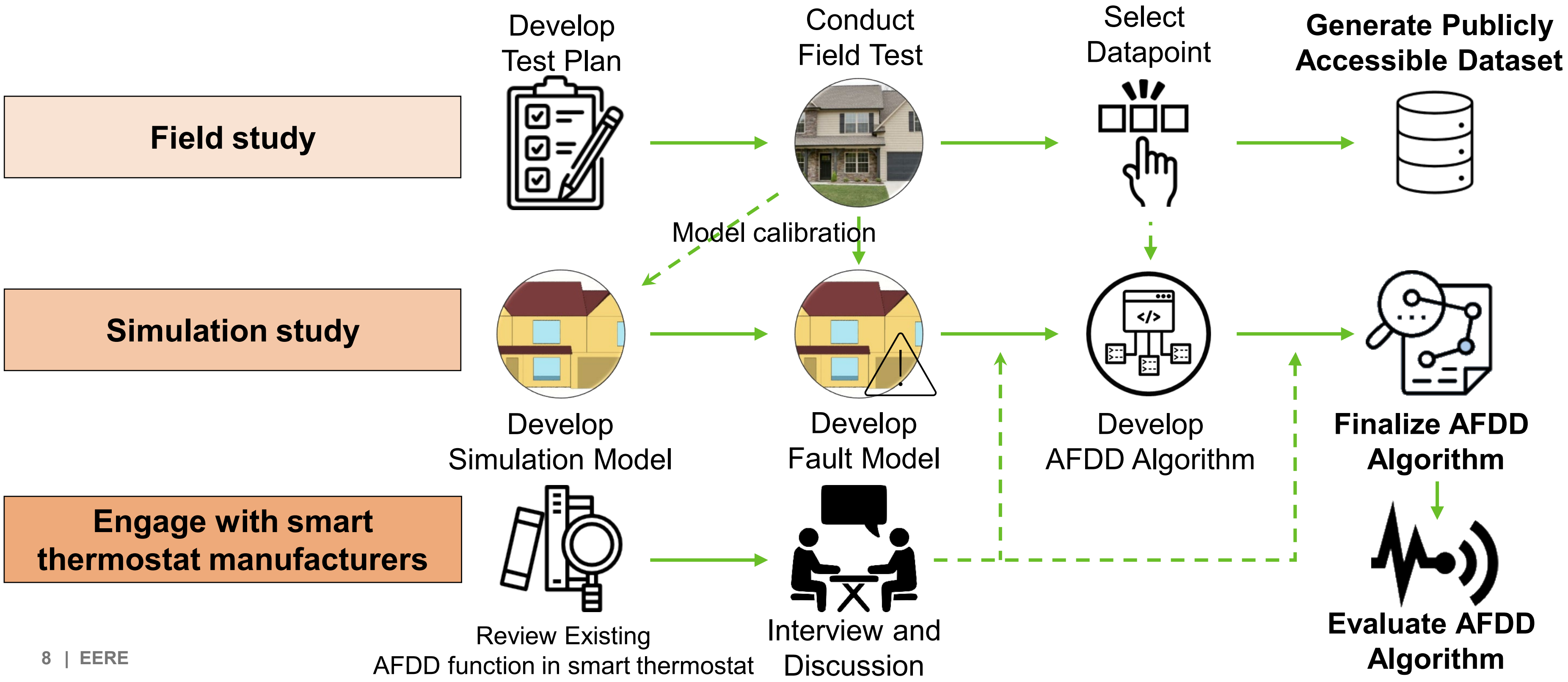
Approach

The project focuses on generating fault-free and fault data to formulate, develop, and evaluate a cost-effective, data-driven residential AFDD algorithm.

Main goals:

- **Analyze fault-free and fault data**
  - Collect and analyze data under normal operating conditions (fault-free) and various fault conditions as a foundation for model development
- **Develop refrigerant fault EnergyPlus simulation model**
  - Develop model and calibrate/validate with field test data
- **Develop cost-effective AFDD algorithm**
  - Develop cost-effective residential AFDD models that rely exclusively on data collected from smart thermostats and smart meters, ensuring cost-effectiveness by using readily available sensors and data sources
- **Demonstrate AFDD algorithm's effectiveness**
  - Validate algorithm's effectiveness in terms of accuracy of fault detection, energy efficiency, and occupant comfort through field experiments, showing its potential for real-world applications

Approach Technical work plan



Approach Field study

- ORNL's Yarnell Station research house for test and data generation
  - 3 ton single-stage HP system with dual zone control
  - Occupancy-emulated and well-instrumented for performance monitoring

Yarnell Station research house
(located in Knoxville, Tennessee)

Conditioned area	2,400 ft^2
Built year	2009
Number of floors	2
Number of bedrooms	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

Approach Simulation study

- Develop calibrated model for Yarnell Station house
  - To produce training data for developing the FDD model
  - To perform scaled analysis in different climate locations

Rendering of building energy simulation model for Yarnell Station

- **Weather file generation**
  - Outdoor air temperature
  - Solar radiation
- **Building energy model development**
  - Drawings
  - Indoor air temperature
  - HVAC system-related data (e.g., supply air temperature)
  - Energy consumption
- **Fault model development**
  - Correlations between fault level and system efficiency
  - Correlations between fault level and data points selected to detect refrigerant faults

Approach Engage with smart thermostat manufacturers

- Purposes of interviewing smart thermostat manufacturers
  - To **understand current status** of existing FDD functions in residential smart thermostats
  - To **identify barriers** to implementing new FDD functions in existing residential smart thermostats
  - To **receive feedback** on team's research direction
  - To **develop reliable, cost-effective residential AFDD algorithm** that can be implemented in existing thermostats

Approach Overcome barriers and challenges of developing reliable, cost-effective residential HVAC AFDD function

Overcoming cost barriers:

- Proposed AFDD algorithm will use minimal set of sensors or rely on sensor data already collected by installed smart thermostat or smart meter
- Approach reduces need for additional sensors and lowers monitoring costs by leveraging capabilities of installed smart thermostat and smart meter

Implementing FDD function in smart thermostats:

- Meetings conducted with smart thermostat manufacturers
- Meetings focus on research directions, design and functionality of the AFDD feature, and feasibility of implementation in smart thermostats

Progress and Future Work

Test scenarios

Scenario	Undercharge fault	Overcharge fault
Baseline test	7/8/2024–7/15/2024	
Scenarios	−10% (6/5/2024–6/11/2024)	+5% (7/15/2024–7/22/2024)
	−20% (6/11/2024–6/17/2024)	+10% (7/22/2024–7/29/2024)
	−30% (6/17/2024–6/24/2024)	+15% (7/29/2024–8/5/2024)
	−40% (6/24/2024–7/2/2024)	+20% (8/5/2024–8/12/2024)
	−50% (7/2/2024–7/8/2024)	+25% (8/12/2024–8/19/2024)

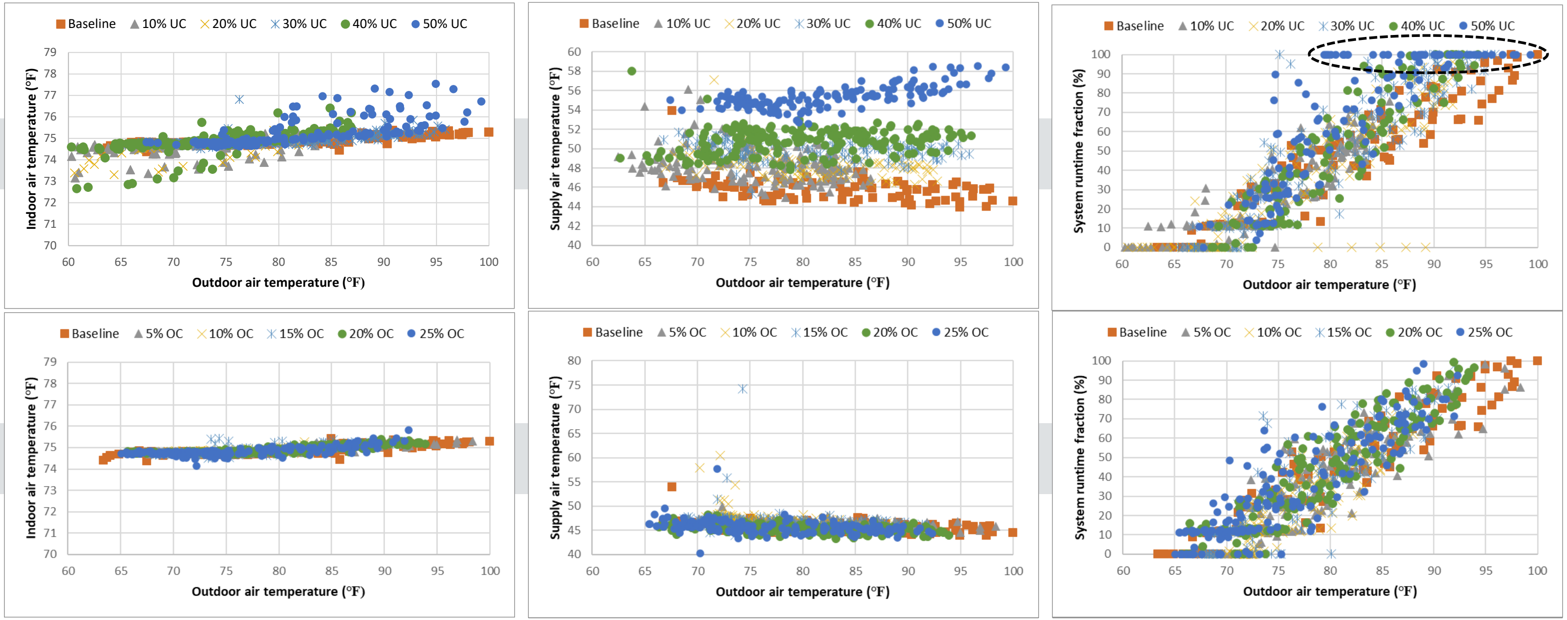
Data points

- Outdoor conditions
  - Outdoor air temperature
  - Outdoor air relative humidity
- Building indoor conditions
  - Indoor air temperature
  - Indoor relative humidity
- HVAC system
  - Supply air temperature
  - Supply air relative humidity
  - Supply airflow rate
  - System runtime fraction
  - Suction pressure
  - Energy consumption (outdoor fan, indoor fan, compressor)
- Data resolution: every 15 s

Progress and Future Work Preliminary field data analysis

Refrigerant undercharge fault

Refrigerant overcharge fault



Indoor air temperature Supply air temperature Runtime fraction

- Changes in thermal comfort are difficult to notice with low-intensity refrigerant undercharge (−10% to −30%) or overcharge faults
- Supply air temperature and runtime fraction increase as refrigerant undercharge fault level increases

Progress and Future Work

Meetings with smart thermostat manufacturers

Company	Representative	Status
1	A	Ongoing
2	**B**	**Interviewed**
	C	**Interviewed**
3	D	Ongoing
	E	Ongoing
	F	**Interviewed**
4	**G**	**Interviewed**
	H	**Interviewed**
5	**I**	**Interviewed**
6	J	Ongoing

Discussion Points

- **General discussions**: direction of projects, barriers, industrial viewpoint
- **Specific questions**

  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?

- As of September 2024, ten representatives involved in smart thermostat development at six different smart thermostat and HVAC manufacturers were contacted
  - ➢Five interviews (six representatives from four different smart thermostat and HVAC manufacturers) were conducted; process is ongoing

Progress and Future Work

Meetings with smart thermostat manufacturers

General discussions

01. All interviewees agreed with our research direction focused on importance of developing a cost-effective HVAC AFDD function for residential buildings

02. Selecting a minimal set of data points to ensure fault detection accuracy while minimizing costs is crucial

03. Long payback period is a significant barrier to implementing HVAC AFDD functions in residential buildings

04. Current AFDD focuses primarily on diagnosing system failures, not on energy efficiency

Specific questions

Q1. **What should be considered when developing AFDD?**

- Occupants are likely to ignore or pay little attention to **fault alarms**
- **Balancing precision and recall** in fault detection to avoid unnecessary alerts is crucial
- **Appropriate data interval must be determined** considering accuracy of AFDD and data processing performance of the smart thermostat

Progress and Future Work

Meetings with smart thermostat manufacturers

Q2. Which fault can be detected?

- Undercharge and overcharge of refrigerant, airflow rate, and system breakdown

Q3. What types of data are used for fault detection?

- Environmental (temperature, humidity, airflow rate) and system (refrigerant status, runtime fraction)

Q4. What data can be crucial in improving accuracy of fault detection?

- Real-time energy data, outdoor and indoor air temperature, indoor humidity, supply air temperature, setpoint temperature, and system runtime rate

Q5. Can additional sensors be connected to an existing smart thermostat?

- Directly connecting third-party sensors to a smart thermostat can be challenging owing to protocol compatibility issues; however, data acquisition may be possible using wireless communication

Progress and Future Work

Future work

- Heating season refrigerant under and overcharge tests with baseline operation
- High-fidelity EnergyPlus model development; calibration with cooling and heating season test results
- Data and sensitivity analyses for sensor and meter selection (optimal/minimal set of sensors/meters and time resolution)
- Rule-based and machine-learning–based FDD algorithms will be developed using optimal/minimal set of data points highly correlated with refrigerant faults, as identified through field tests, to detect refrigerant faults
- The developed AFDD algorithm will be evaluated in different target buildings/communities

Commercialization plan or market impact

- Continue to engage with smart thermostat manufacturers
- Recurring TAG meeting with smart thermostat and HVAC manufacturers to update on progress and discuss research output's impact on market and residential sector

Plans beyond the end of the project

- Continue collaborating with smart thermostat manufacturers to explore opportunities for integrating the developed AFDD algorithm into existing products

Thank you

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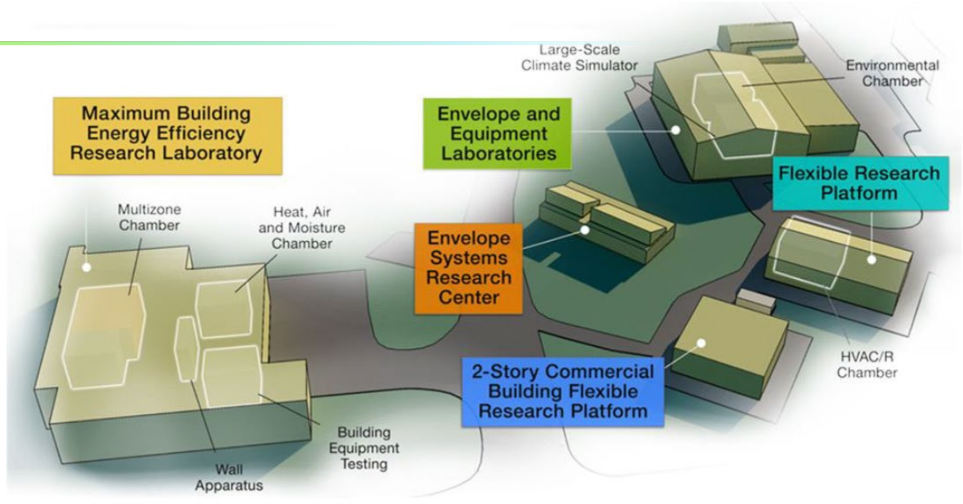

The **Building Technologies Research and Integration Center (BTRIC)** at ORNL has supported DOE BTO since 1993. BTRIC is comprised of more than 60,000 square feet of lab facilities conducting RD&D to develop affordable, efficient, and resilient buildings while reducing their greenhouse gas emissions 65% by 2035 and 90% by 2050.

Scientific and Economic Results
139 publications in FY24
140+ industry partners
60+ university partners
16 R&D 100 awards
64 active CRADAs

BTRIC is a DOE-Designated National User Facility

Reference Slides

Project Execution

	FY 2024				FY 2025				FY 2026			
Planned budget	180,000				TBD				TBD			
Spent budget	140,000											
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q2 Milestone: Data Collection Plan												
Q3 Milestone: Generate Fault-Free and Fault Data												
Go/No-Go Decision: Survey or Meeting with Smart Manufacturers												
Q4 Milestone: Analyze the Field Data												
Current/Future Work												
FY25 Q1 Milestone: Conduct Field Test (Heating and Cooling Season)												
FY25 Q2 Milestone: Data Analysis and Identify Variables for FDD Algorithm												
FY25 Q3 Milestone: Develop/Calibrate Building Energy Simulation Model												
FY25 Q4 Milestone: Develop Initial Residential AFDD Algorithm												
FY26 Q1 Milestone: Generate Publicly Accessible Field Dataset												
FY26 Q2 Milestone: Evaluate the Residential AFDD Algorithm												
FY26 Q3 Milestone: Engage with Smart Thermostat Manufacturers												
FY26 Q4 Milestone: Finalize the Residential AFDD Algorithm												

- Go/no-go decision points: Survey or meeting with smart technology manufacturers
  - ➢ ORNL team had five meetings with six representatives from four smart thermostat manufacturers.
- There are no slipped milestones

Team

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