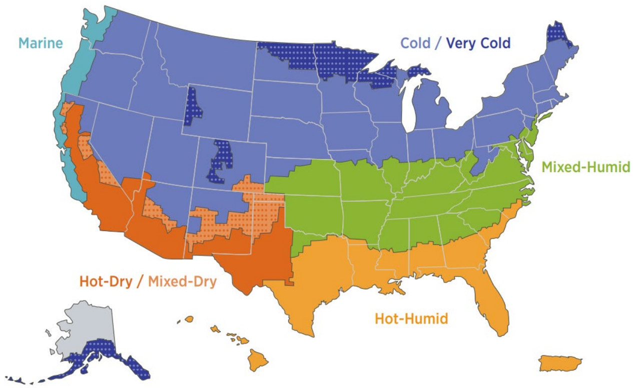
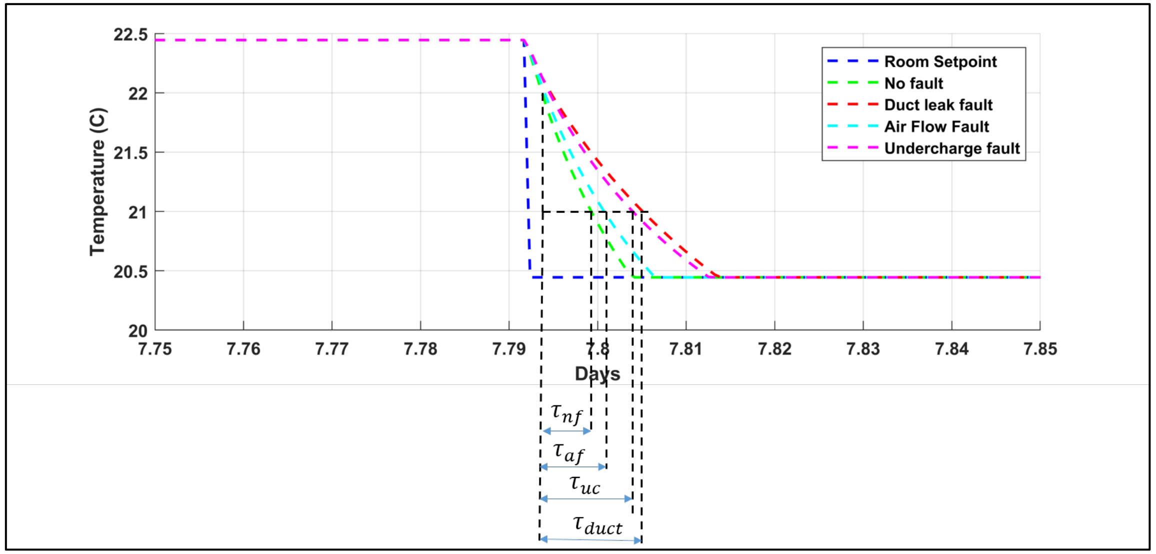
Develop field test methods and analytical techniques to assess HVAC fault impacts and a simplified commissioning method

Building America
U.S. DEPARTMENT OF ENERGY





National Renewable Energy Laboratory
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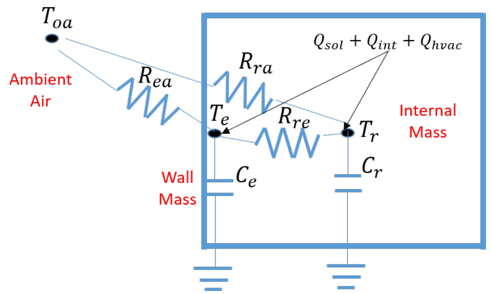
WBS #1.2.2.62

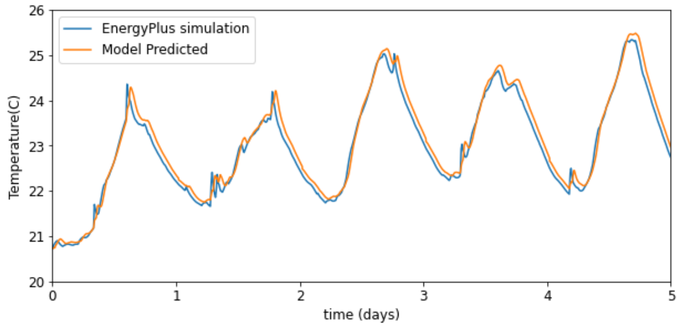
Project Summary

Objective and Outcome

The objective of this project is to drastically improve the installed performance of residential HVAC equipment by:

1. Developing field and analytical methods to measure and assess the impact of installation-related faults
2. Developing a low-cost, automated fault detection algorithm using only thermostat data





Team and Partners

- NREL – Jon Winkler, Rohit Chintala, Lena Burkett, Xin Jin, Sugi Ramaraj
- FSEC (Eric Martin) and UNL (David Yuill)
- Ecobee
- ACCA

Stats

Performance Period: FY19 – FY22

DOE budget: $1,025k (~$256k/y) Cost Share: $0k

Milestone 1: Journal paper on fault detection method

Milestone 2: Field study design document to align BA FOA performers field data on HVAC system faults

Milestone 3: Journal article on a sensitivity analysis on the accuracy of the fault detection algorithm

Outline

- Problem Statement, Impact, and Overall Approach

Project Focused on Two Main Efforts:

- Assessing the Impact of Residential HVAC Installation Faults

- An Automated Method to Improve Installation Quality

Problem

- It is estimated that more than **65% of residential HVAC systems** have been **improperly installed or are performing sub-optimally** resulting in equipment consuming **approximately 20%–30% more energy** than necessary [1, 2, 3]
- Current **residential AFDD does not exist on most equipment**
  - After market **solutions are expensive and challenging to deploy** [4]
- Residential **equipment replacements are often not properly sized** based on load calculations [5]

> ***"Continued pursuit and support of HVAC quality installation is needed, but new approaches may be required."***
>
> DOE, 2018. *Residential HVAC Installation Practices: A Review of Research Findings*.

Project Focus

Example Fault Type	Installation/ Service	Operational
Indoor unit airflow rate	X	X
Outdoor unit airflow rate		X
Refrigerant undercharge	X	X
Refrigerant overcharge	X	
Presence of non-condensable gases	X	
Liquid line restriction	X	
Compressor valve leakage		X
Equipment sizing	X	
Duct leakage	X	X

[1] DOE, 2018. Residential HVAC Installation Practices: A Review of Research Findings.
[2] Domanski et al. 2014. Sensitivity analysis of installation faults on heat pump performance.
[3] Lstiburek and Petit, 2010. Expert Meeting for Diag. and Perf. Feedback for Res. Space Conditioning Equip.
[4] Winkler, Munk, and Hunt. 2022. Barriers to Broader Utilization of Fault Detection Technologies for Improving Residential HVAC Equipment Efficiency
[5] Personal communication with Air-Conditioning Contractors of America

Alignment with EERE BTO Goals

BTO Decarbonization Goals

"Support rapid decarbonization of the U.S. building stock in line with economy-wide net-zero emissions by 2050 while centering equity and benefits to communities."

- Increase Building Energy Efficiency: Reduce onsite energy use intensity in buildings by 30% by 2045 and 45% by 2050, compared to 2005
- Accelerate Building Electrification: Reduce on-site fossil-based CO2 emissions in buildings 25% by 2035 and 75% by 2050, compared to 2005
- Transform the Grid Edge at Buildings

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Heat Pumps

Heat Pumps

Heat Pumps

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Heat Pumps

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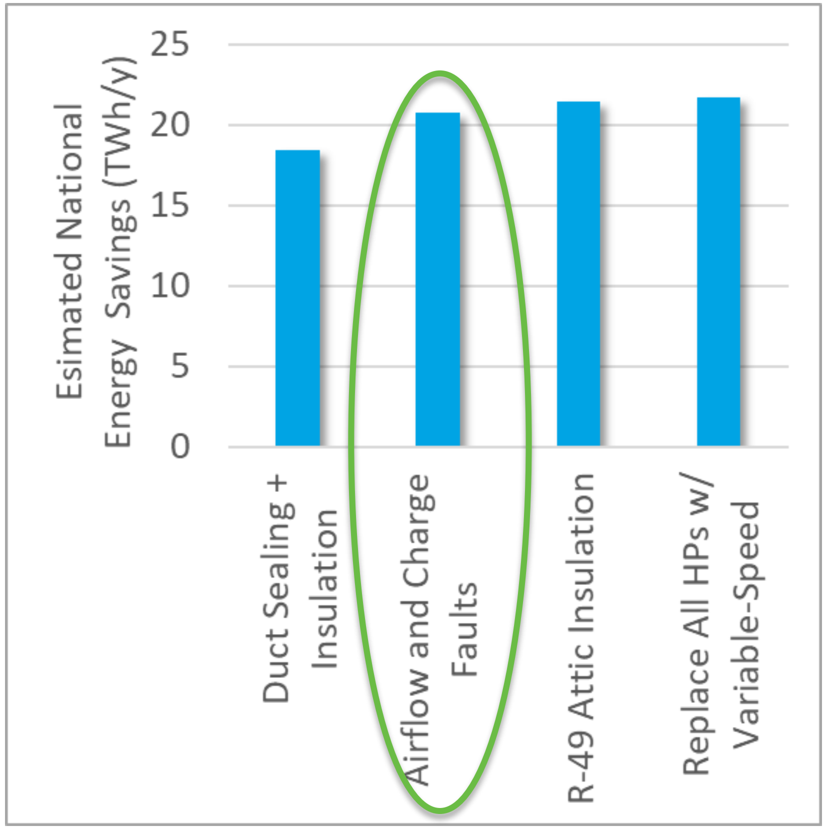
Heat Pumps

Ensuring residential HVAC installation quality is critical to achieving DOE's equitable decarbonization goals.

Potential Impact

- **Indoor airflow and refrigerant charge faults** in residential air conditioners and heat pumps **waste ~21 TWh/y of site energy** costing homeowners more than **$2.5 billion annually** [1]
- **Solving indoor airflow and refrigerant charge faults could save as much or more energy than common existing programs** [1, 2]
  - On average, **8% and 13% energy increase for air conditioners and heat pumps**, respectively, due to airflow and charge faults alone
- Assumptions/caveats from 2020 study:
  - Only include central ACs and HPs in single-family, detached homes
  - Heat pump market penetration based on 2009 EIA data
  - Fault prevalence data was based on old studies



Energy wasted due to installation faults could increase significantly as heat pumps become more common.

[1] Winkler et al. 2020. Impact of Installation Faults in Air Conditioners and Heat Pumps in Single-Family Homes on US Energy Usage.
[2] Wilson et al. 2017. Energy Efficiency Potential in the US Single-Family Housing Stock. National Renewable Energy Laboratory.

Overall Approach

Two main approaches to addressing this problem

1. Building America fault prevalence field study
   - Hypothesis: Testing HVAC performance in the field will yield actionable information about the prevalence and severity of installation faults
   - Outcome: Industry and programs can confidently invest in and implement tools and practices to deliver quality installation, now knowing the real-world savings potential

2. Development of a simplified, automated method to improve installation quality
   - Hypothesis: Indoor temperature data collected by a thermostat along with weather data can be used to learn house characteristics and detect air conditioner installation faults
   - Outcome: Low-cost, automated method for detecting residential HVAC installation and operational faults

Assessing the Impact of Residential HVAC Installation Faults

Building America Fault Prevalence Field Study – Overview

Field testing of 400 newly installed residential HVAC systems

- Central ducted split systems
- Air conditioner or air source heat pump
- Installed within the past year

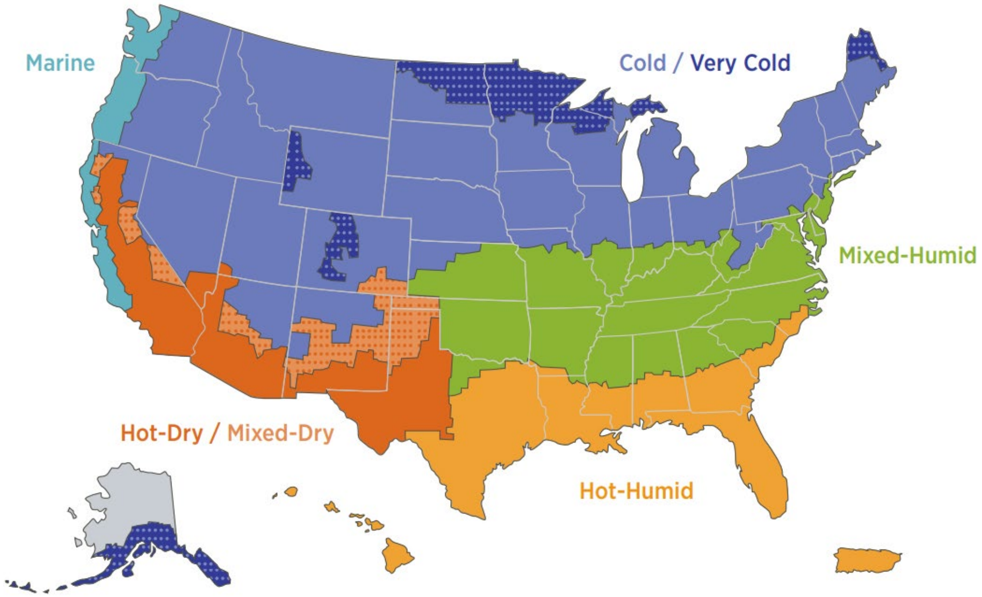
Performance parameters/faults of interest

- Indoor unit performance: airflow rate, static pressure, etc.
- Refrigerant charge
- Refrigerant non-condensable gases
- Duct leakage
- Control configuration

NREL's role

- Ensure consistent and accurate field test methodologies
- Combine dataset and analyze national impact

Results expected late 2023



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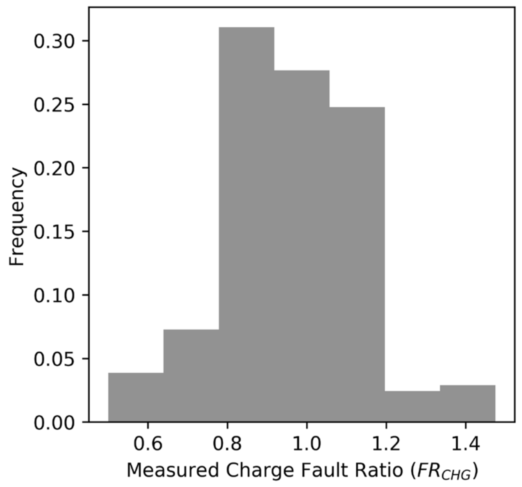
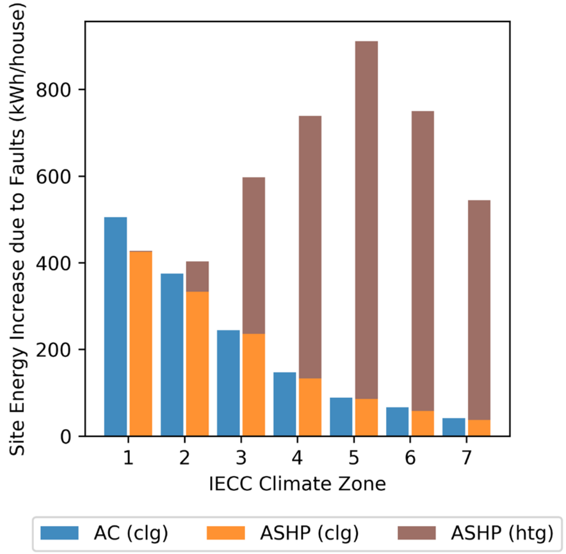
National Impact Analysis Approach (Previous Work)

Fault prevalence data + Correlation between fault level and efficiency + Annual building models = Estimated annual energy savings potential

- Fault prevalence data
  - How common?
  - How severe?
  - *Past field studies*
- Correlation between fault level and efficiency
  - *Generalized correlations based on laboratory data*
- Annual building models
  - NREL ResStock





Future Work

- Utilize Building America study fault prevalence data to update ResStock fault intensity histograms and account for additional fault types
- Update fault impact correlations using recent UNL laboratory data when multiple faults are present
- Investigate fault impacts with increased cold climate heat pump deployment

An Automated Method to Improve Installation Quality

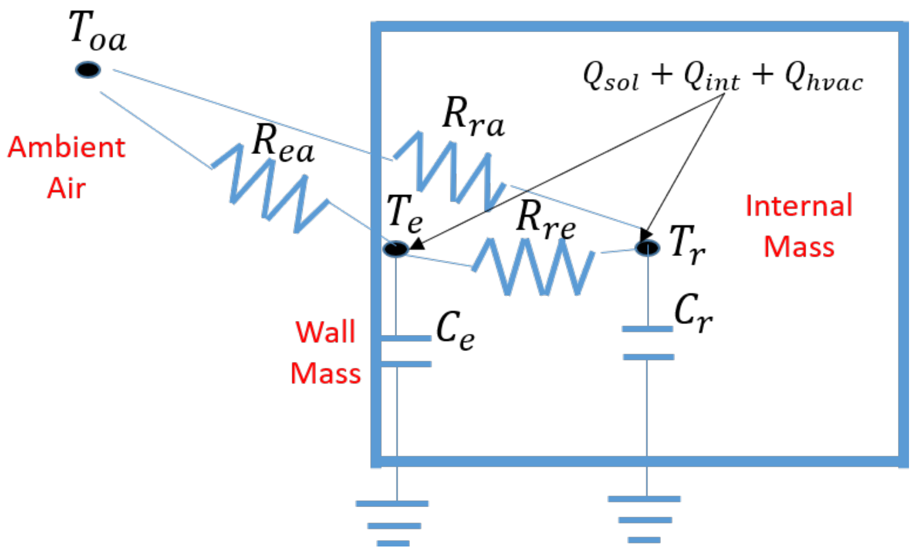
Our Approach – Low Cost AFD Algorithm

A Low-Cost Fault Detection System for Widespread Implementation

- Data required for fault detection can be easily collected via room temperature thermostat and outdoor weather information from a local station
- Easily affordable as it can be embedded in existing smart/connected thermostats with very low retrofitting costs compared to adding or embedding sensors

Simple Implementation

- Building specific information needed is minimal. The algorithm uses:
  - Two months worth historical data of room temperatures, rated cooling capacity, and historical outdoor air temperature and global horizontal irradiation
- Detects faults early and alerts homeowner to take remedying action



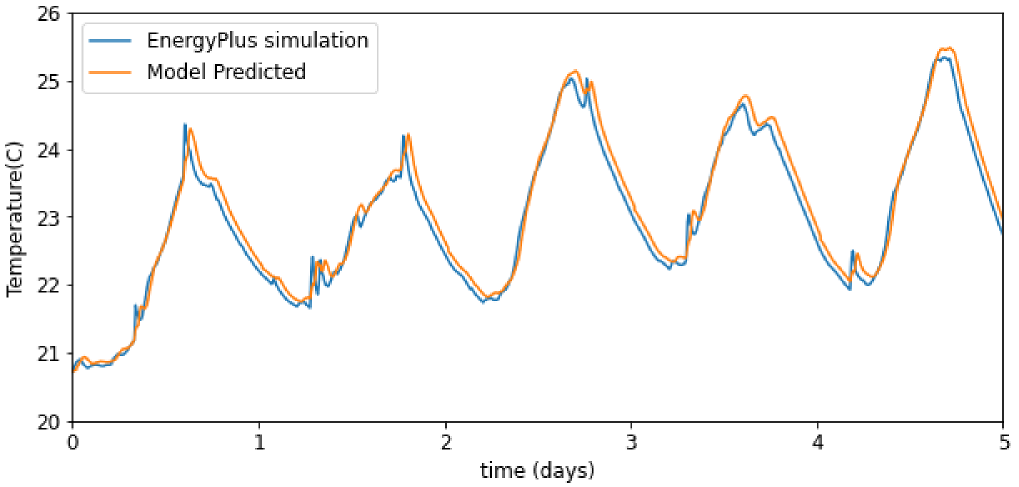
An Automated Method to Improve Installation Quality – Overview

3R2C Building Thermodynamics Model

- Building parameters are identified using historical data when the air-conditioning has cycled off
- Several candidate models are tested with various simulation timesteps and prediction horizons to select the best model

3R2C parameter set θ

C_r: Room air thermal capacitance
C_w: Equivalent wall thermal capacitance
α: GHI proportionality constant
R_{re}: Room to wall thermal resistance
R_{ra}: Room to outdoor thermal resistance
R_{ea}: Room to outdoor thermal resistance



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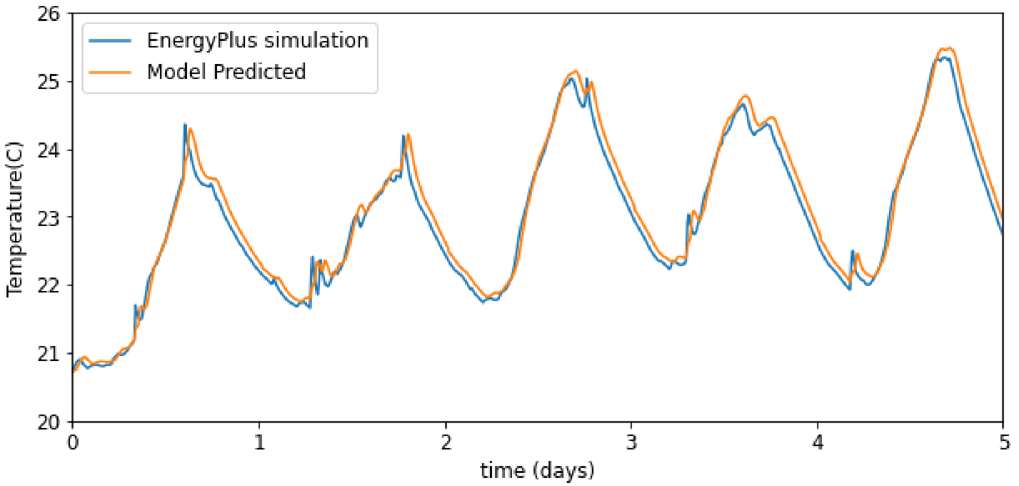
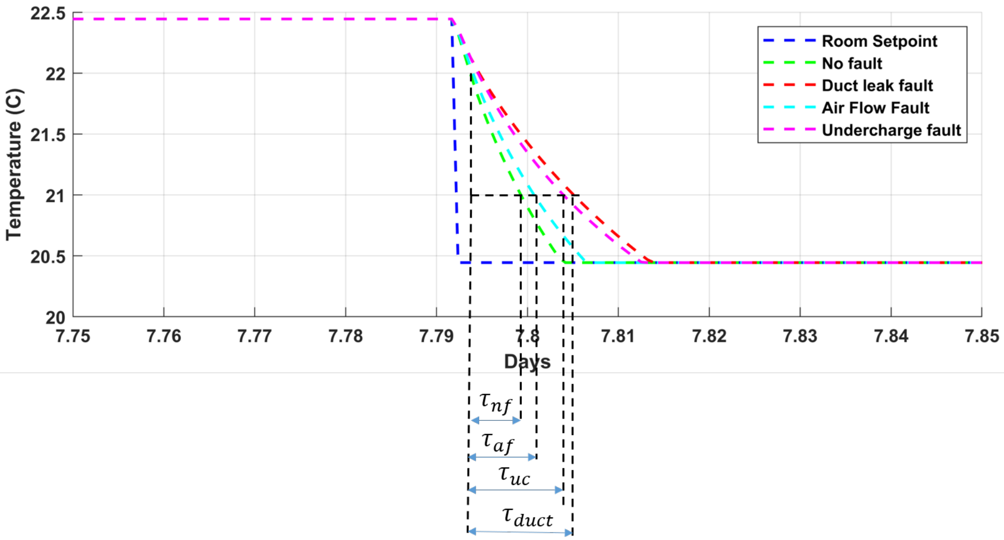


Fault Detection Using Thermostat Drive Cycles



- A thermostat drive cycle experiment raises the temperature by 2°C and then lowers the temperature back to the original setpoint
- Time required to lower the room temperature by 1°C constitutes τ_meas. 3R2C model parameters are then used to compute τ_pred and τ_20f.
- When τ_meas > τ_20f, it indicates the presence of a fault

Current Solutions and Available Technology

- Residential HVAC FDD technology is a complex market landscape with a variety of technology types and features
  - See Winkler, Munk, and Hunt. (2022). Barriers to Broader Utilization of Fault Detection Technologies for Improving Residential HVAC Equipment Efficiency

OEM Embedded – Installed on-board during manufacturing	3rd Party – Add-on sensors after/during equipment installation
Occupant Safety • Prevent operation if unsafe for occupants • Availability: Forced air furnaces ✓ Installation faults ✓ On-going faults ❑ Diagnostics $	**Installer Smart Tools** • Refrigerant gauge sets that include FDD • Availability: Widely available at cost premium ✓ Installation faults ❑ On-going faults ✓ Diagnostics $
Equipment Reliability • Ensures equipment is not damaged during operation • Availability: Premium air conditioners and heat pumps ✓ Installation faults ✓ On-going faults ❑ Diagnostics $$	**Permanently Installed Sensor Set** • Professionally-installed continuous monitoring • Availability: Limited number of products ❑ Installation faults ✓ On-going faults ❑ Diagnostics $$$
Prescriptive-Based • Detects specific faults using on-board measurements • Availability: Limited premium air conditioners and heat pumps ✓ Installation faults ✓ On-going faults ✓ Diagnostics $$$	**Single-Point Monitoring** • Monitors trends in energy use, equipment runtime, etc. • Availability: Energy monitors, smart thermostats ❑ Installation faults ✓ On-going faults ❑ Diagnostics $
Performance-Based • Triggers faults if equipment performance is lower than threshold • Availability: Not currently available ✓ Installation faults ✓ On-going faults ❑ Diagnostics $$$	

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Project Focus

Progress – Development Steps

FY 19: Ideation and Algorithm Proof of Concept → **FY 20: System Identification and Algorithm Robustness** → **FY 21: Verification Using Real-World Data** → **FY 22: Design Load Estimation**

FY 19: Ideation and Algorithm Proof of Concept

- Literature review and gap identification
- Initial algorithm proof of concept developed using simulated data
- Single house, ranging fault types/intensities
- Journal article #1 drafted

FY 20: System Identification and Algorithm Robustness

- Sensitivity study using simulate data
- Improved system identification accuracy
- Tested algorithm robustness across a variety of cases

FY 21: Verification Using Real-World Data

- Validated thermodynamic models for over 50 homes using thermostat data
- Verified fault detection algorithm using lab home data
- Journal article #2 drafted

FY 22: Design Load Estimation

- Developed methodology to estimate design cooling load using thermostat data
- Implemented and evaluated approach using simulated data
- Journal article #3 drafted

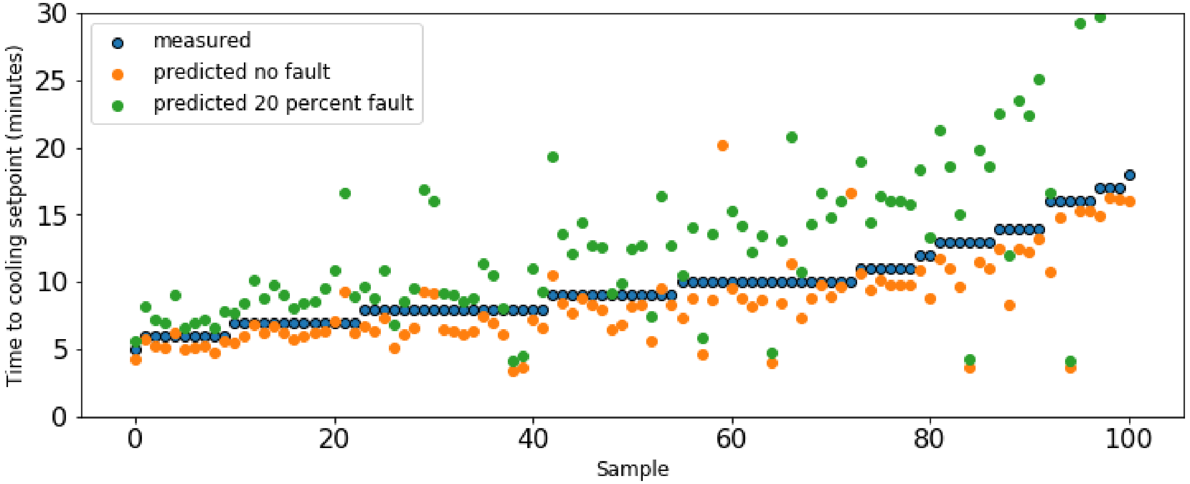
Ideation and Algorithm Proof of Concept (FY 19)

Fault Determination After Several Thermostat Drive Cycle Tests

- Determination of fault presence is done by running thermostat drive cycle tests
- When τ_{meas} is consistently greater than $\tau_{pred,20f}$, a fault is present
- When no fault is present, then τ_{meas} is much closer to $\tau_{pred,nf}$

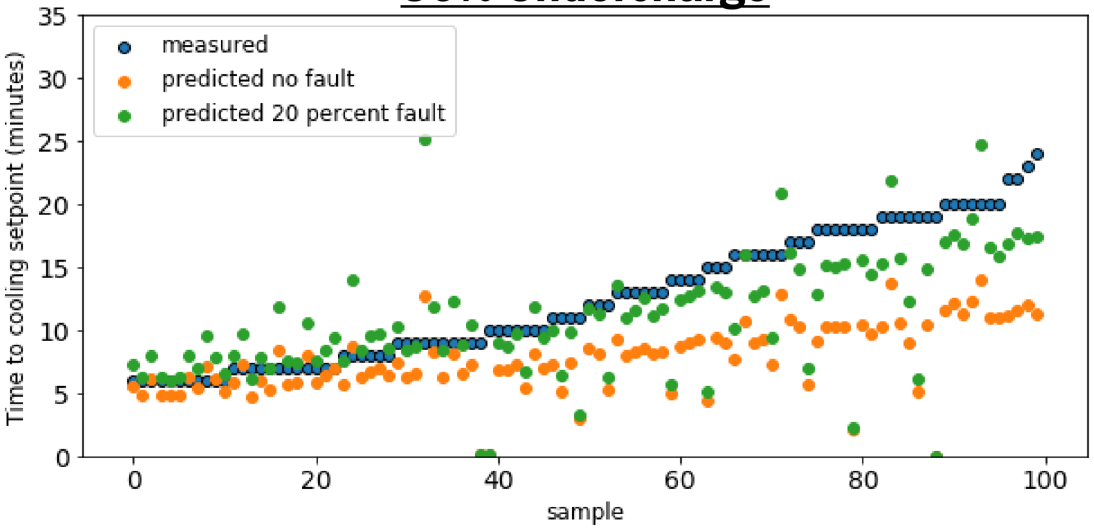
Publication: Chintala, R.; Winkler, J; Jin, X.; (2021). "Automated fault detection of residential air-conditioning systems using thermostat drive cycles," Energy and Buildings, 236, 110691

No-Fault Case



- "Measured data" for an individual drive cycle test
- Predicted time to cooling setpoint without a fault
- Predicted time to cooling setpoint w/ 20% lower cooling capacity

30% Undercharge



When a fault is present, measured time to cooling setpoint (blue) is closer to the predicted case with an assumed fault impact (green).

System Identification and Algorithm Robustness (FY 20)

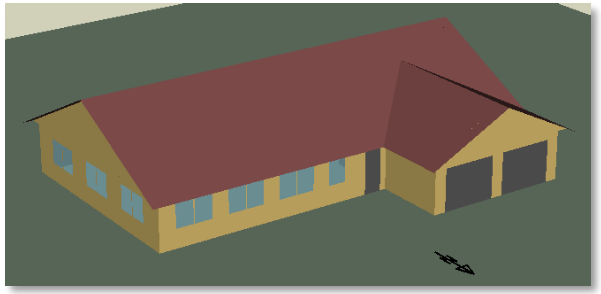
Testing Robustness of AFD Algorithm

- AFD should be accurate for homes with varying construction
- Nine EnergyPlus with varying thermal heat capacitance, thermal heat resistance, building air-tightness, and solar heat gain

Sensitivity Analysis of AFD Algorithm

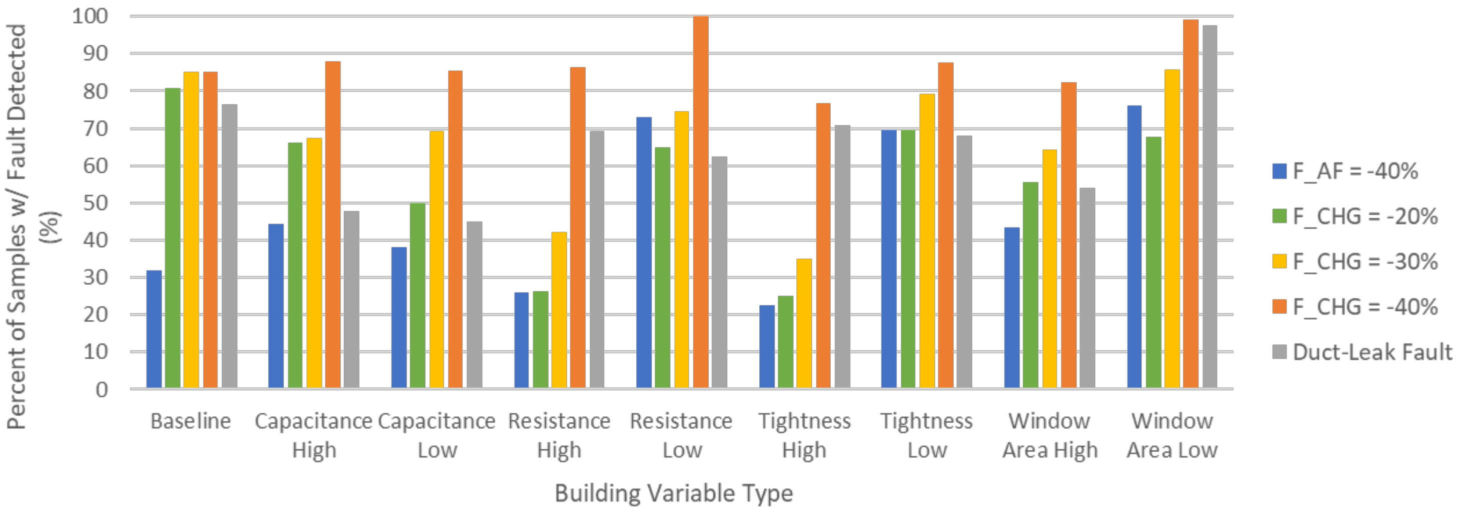
- High success rate in detecting undercharge faults greater than equal to 30% and duct faults
- Lower accuracy for airflow faults since impacts on cooling capacity were smaller

Publication Pending: Chintala, R., et al; (2023). "Sensitivity analysis of an automated fault detection algorithm for residential air-conditioning systems," Applied Thermal Engineering, In Review.



Simulated house geometry

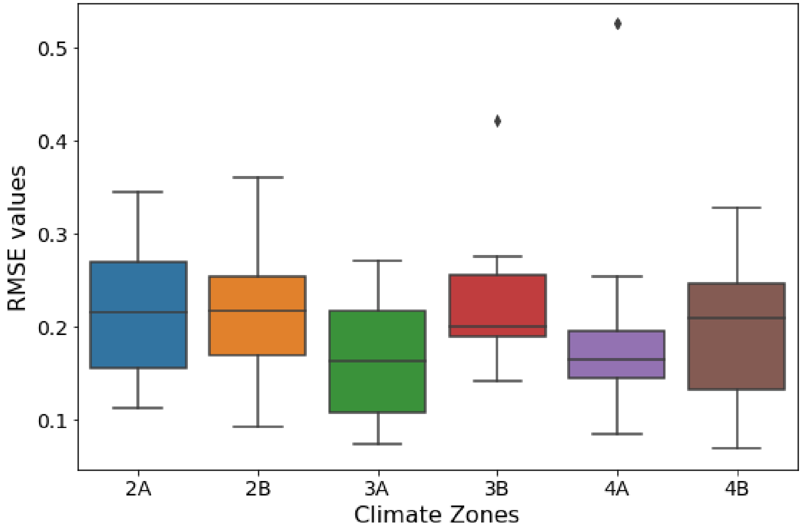
Building Model Input Parameter	Low	Baseline	High
Wall resistance, $\left(h \cdot ft^2 \cdot \frac{R}{Btu}\right)$	4.0	10.9	16.0
Ceiling resistance, $\left(h \cdot ft^2 \cdot \frac{R}{Btu}\right)$	2.1	20.2	61.3
Drywall capacitance, $\left(\frac{Btu}{R \cdot ft^2}\right)$	None	0.42	0.83
Building airtightness (ACH_{50})	25	15	5
Window Area (m^2)	1.34	1.75	2.32



Verification Using Real-World Data (FY 21)

System Identification Model

- High accuracy thermodynamic models are developed from real-home data with a root-mean-squared error less than 0.4°C for all homes considered
- Validation was performed using thermostat data from 90 homes– 15 homes in 6 climate zones
- Data sets were constructed by considering subsets of time when the AC system had cycled off



RMSE values between the predicted and measured indoor temperature for all buildings by IECC climate zone

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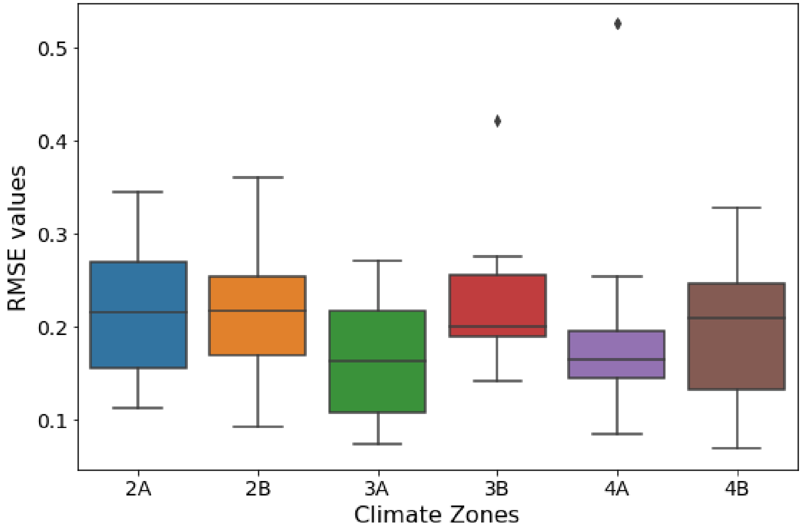


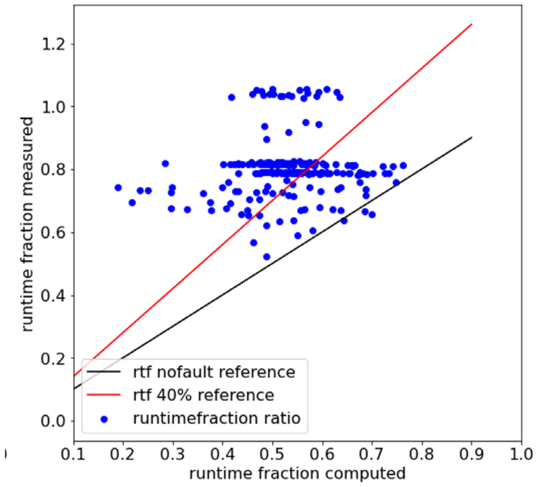
RMSE values between the predicted and measured indoor temperature for all buildings by IECC climate zone

Fault Detection Verification

- AFD algorithm validated on a real laboratory home collected by FSEC on an AC with faults imposed
- Algorithm successfully detected all imposed faults
- Detection accuracy on the drive-cycle tests:
  - 30% undercharge – 70.6%
  - 30% undercharge + 11% duct leakage – 85.2%
  - 11% duct leakage – 69.1%

West Control Home

East Experimental Home



30% undercharge

$n_{samples} = 245,$

$accuracy = 70.6\%$

Design Load Estimation (FY 22)

Objective

- Leverage gray-box building model approach used for fault detection algorithm to calculate the design cooling load

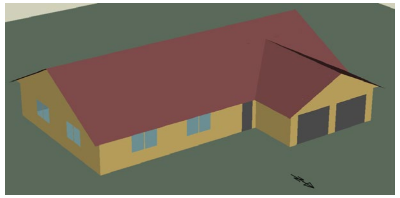
Motivation and Benefits

- Accurate estimates of design cooling load required to properly size the air-conditioning system
- Traditional methods are time intensive, complicated, and sensitive to assumptions

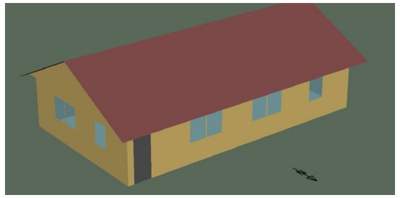
Simulation Study

- Generated data using EnergyPlus models for typical, existing construction and new construction houses in 7 cities/climates
- The average error over the 14 homes was less than 30% when compared with EnergyPlus
- Efforts to improve the accuracy for the other homes is currently ongoing

Publication Pending: Chintala, R.; Winkler, J; Ramaraj, S; Jin, X.; (2023). "Sensitivity analysis of an automated fault detection algorithm for residential air-conditioning systems," Applied Thermal Engineering, In Review.



Geometry A



Geometry B

Summary of the design loads computed using the 3R2C algorithm for existing homes

City	Climate Zone	Computed Design Load (kW)	EnergyPlus Average "Design" Load (kW)	Percentage Error
Miami	1	4.26	5.00	-14.8%
Orlando	2a	3.46	5.22	-33.7%
Phoenix	2b	4.74	4.62	2.6%
Atlanta	3a	2.89	5.01	-42.3%
Las Vegas	3b	4.52	4.46	1.3%
Nashville	4a	2.78	3.40	-18.2%
Albuquerque	4b	2.82	3.06	-7.8%

Future Work

- Algorithm improvements
  - Rigorous testing of the algorithm in real-world operation to improve confidence in the fault detection accuracy
  - Improve the accuracy of the system identification by adopting better models to account for solar heat gain through the windows and walls and occupancy and internal convective heating
  - Finding relationship between loss in cooling capacity of air-conditioning system and fault detection accuracy to set up better thresholds
  - Sensitivity analysis of the algorithm in real-world operation under different weather conditions, climate zones, home construction and geometry
- Continue working on opportunities for commercialization

Thank You

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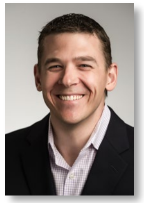
REFERENCE SLIDES

Project Execution

	FY2019				FY2020				FY2021				FY2022			
Planned budget	$300k				$300k				$425k				$0k			
Spent budget	$166k				$209k				$328k				$222k			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work																
Q1 Milestone: Presentation on proposed field protocol																
Q2 Milestone: Final field protocol																
Q3 Milestone: Presentation on fault detection method																
Q4 Milestone: Draft journal article on fault detection method																
Q5 Milestone: Presentation to w/ collaborators																
Q8 Milestone: Draft journal article on sensitivity study																
Q9 Milestone: Workplan for automating building load calculation																
Q10 Milestone: White paper on fault detection improvements																
Q11 Milestone: Presentation on BA FOA performer field methods																
Q12 Milestone: White paper on automated building load calc																
Q14 Milestone: Draft journal paper on equip sizing algorithm																
Q15 Milestone: White paper on fault detection validation																
Q16 Milestone: Final presentation on fault detection work																

Team



Jon Winkler, PI
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Lena Burkett
- Fault study coordination lead

Sugi Ramaraj
- FD algorithm validation

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Wes Davis
- Load calculation approach advisor

ecobee

Ecobee
- Thermostat data provider