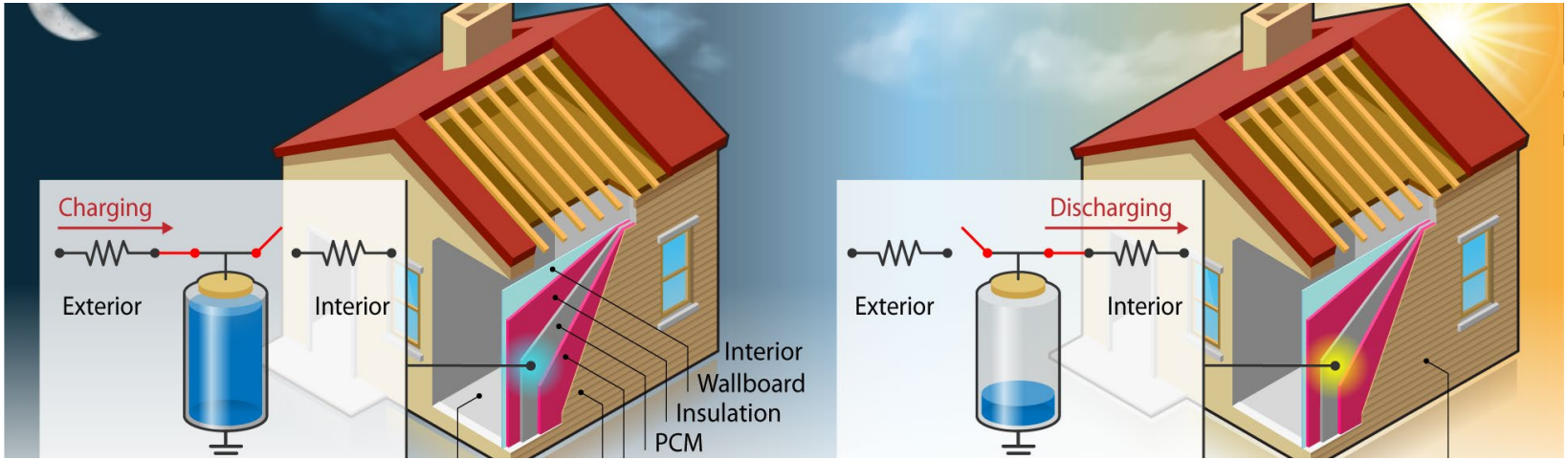
2024 PROJECT PEER REVIEW

U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review: Plug-and-Play Retrofittable Economizer Thermal Switches With Thermal Storage To Reduce HVAC Energy and Enhance Occupants' Comfort

Plug-and-play retrofittable economizer thermal switches with thermal storage to reduce HVAC energy and enhance occupants' comfort



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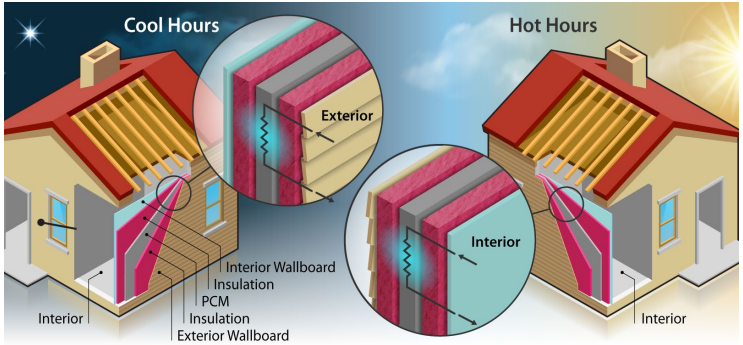
Project Summary

OBJECTIVE, OUTCOME, & IMPACT

Demonstrate plug-n-play thermal switches in form of insertable plugs that can be retrofitted in existing envelopes, thereby reducing HVAC energy and enhancing occupants' comfort, to support achieving DOE's strategic objective "Increase building energy efficiency".



TEAM & PARTNERS

PI: Ravi Kishore, NREL
Key NREL Personnel: Zhiying Xiao, Sajith Wijesuriya, Chuck Booten
External partner: DTE Materials

STATS

Performance Period: Oct 2023- Sept 2025

DOE Budget: $250k (FY24) $172k (FY25)

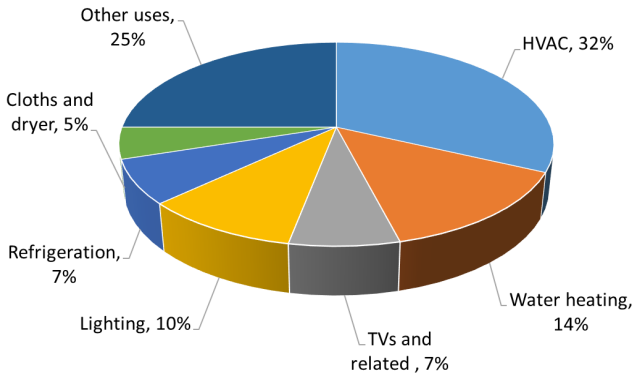
Milestone 1: Numerical model for plug-n-play thermal switch design and performance optimization

Milestone 2: Experimental prototypes confirming thermal performance and effective switching ratio >5

Milestone 3: Cyclability tests demonstrating consistent and reproducible performance

Problem

- HVAC accounts for 30-40% of total energy consumed in buildings
- Energy cost disproportionally affects low-income and disadvantaged communities
- Current Approach:
  - Increase R-value
  - PCM-based thermal storage layer
- Insulation above a certain value can be detrimental:
  - Reduces free ambient cooling/heating
  - Traps internal heat gains
  - Reduces impact of envelope-integrated TES



Source: Residential Energy Consumption Survey (www.eia.gov/consumption/residential/index.php)

Alignment and Impact

- Up to 20% HVAC energy savings predicted due to dynamic envelopes using thermal switches
- HVAC energy savings increases, up to 80% with thermal storage using a thin PCM layer

Cross-cutting goals

Equity: Efficient homes for the LMI and disadvantaged communities

Affordability: Lower energy cost burden and enhanced occupants' thermal comfort

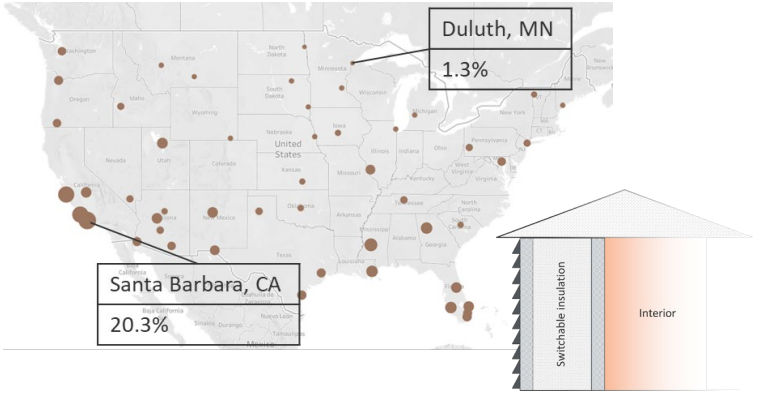
Resilience: Heat resilience during extreme temperature conditions

Strategic objectives

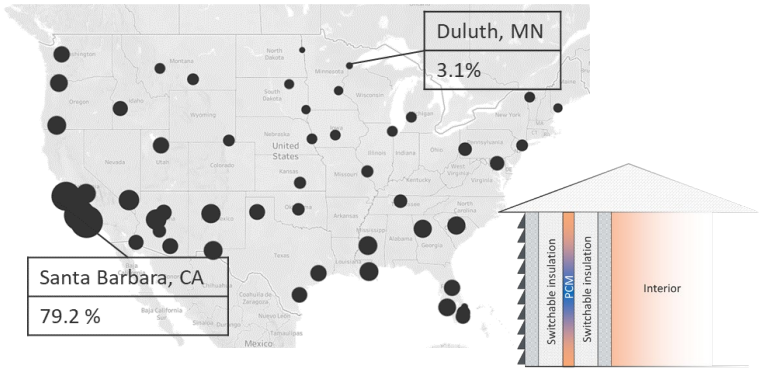
Energy efficiency: Reduce on-site energy use

Grid edge: Demand flexibility using active control

Dynamic insulation only

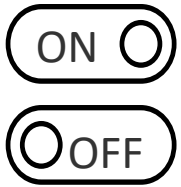


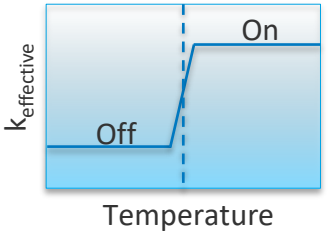
Dynamic insulation + PCM layer

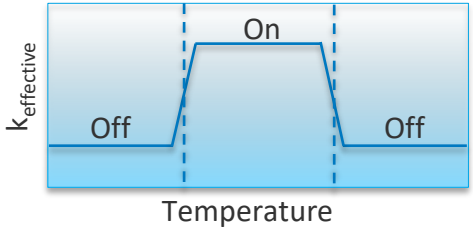


What is a Thermal switch?

- Analogous to an electrical switch, a thermal switch:
  - allows heat flow, when the switch is “on”
  - stops or lessens heat flow when it is “off”
- Thermal switches make envelopes dynamic:
  - OFF State: Low thermal conductivity, when outdoor conditions are unfavorable (too hot or cold)
  - ON state: High thermal conductivity, when outdoor condition is favorable
- Dynamic envelope functions as an economizer, utilizing ‘free’ ambient cooling and heating to reduce building’s thermal load



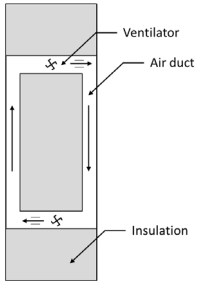




Limitations, concerns, and challenges

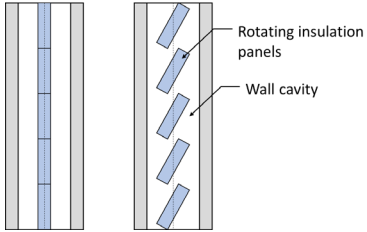
- Technical
  - Switching ratio R_{off}/ R_{on} > 5
  - R_{off} ≈ Rinsulation
- Replaceability
- Retrofit-ability
- Reliability & durability
- Need for external excitation
  - Mechanical
  - Electricity
  - Air-flow
- Cost and payback

Forced convection



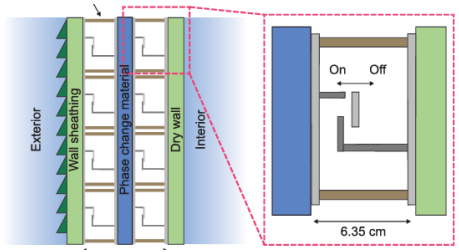
Koenders, Loonen, and Hensen. 2018. Energy and Buildings 173:409-27.

Rotatable fins



Dabbagh and Krarti. 2020. Energy and Buildings 222:110025.

Voltage-driven Tile Thermal Switch



Miao, Kishore, Kaur, Prasher, & Dames. (2022). Cell Reports Physical Science, 3(7), 100960.

Approach

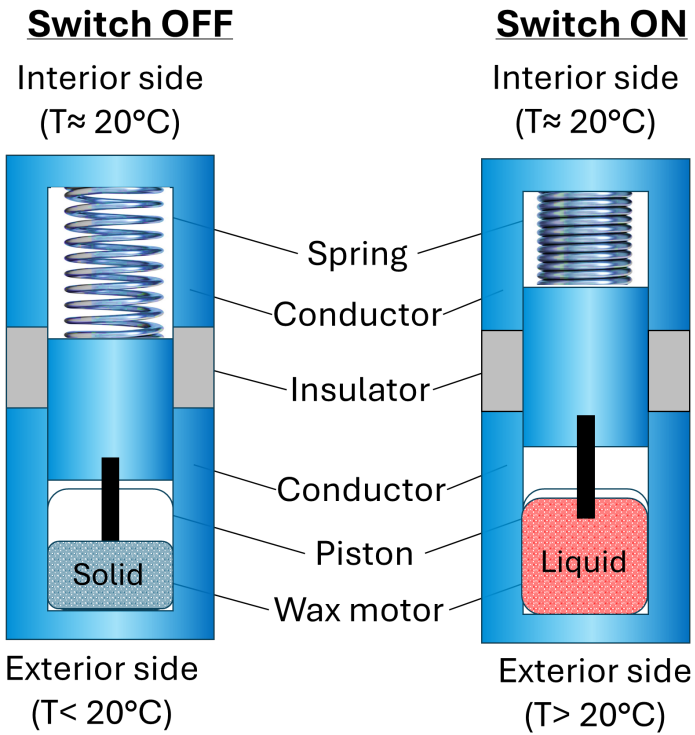
Insertable thermal switches

Design goals

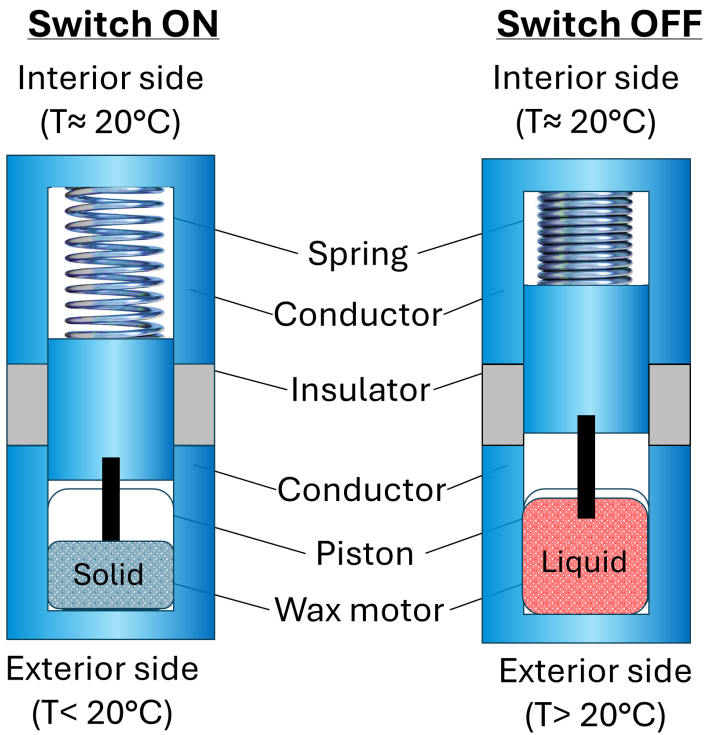
- Insertable and retrofittable
- Durable and reproduceable
- Repairable and replaceable
- Simple installation: drilling, plugging, and sealing
- Cost-effectiveness: Constructed using readily available materials
- Passive operation, needs no/minimal external power
- $k_{on}/k_{off} > 5$ and effective $k_{off} < 0.05$ W/m·K
- 1 switch per ft^2 of envelope surface area

Working principle

(a) Heating dominant climate



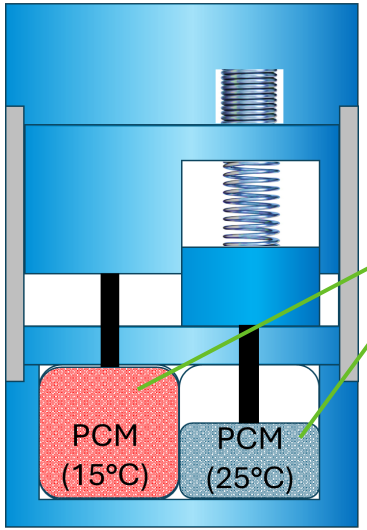
(b) Cooling dominant climate



Working principle

(a) Mixed climate

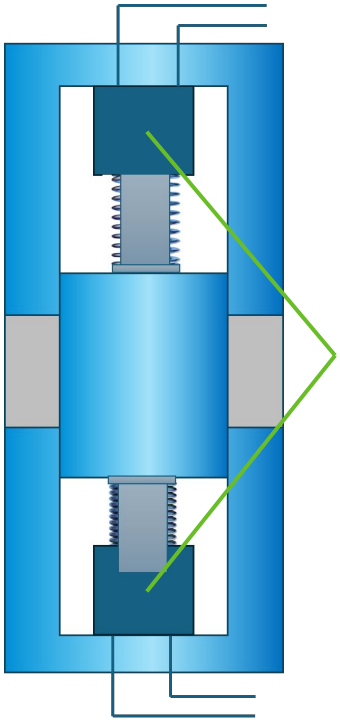
Interior side
(T≈ 20°C)



Exterior side
(15°C > T> 25°C)

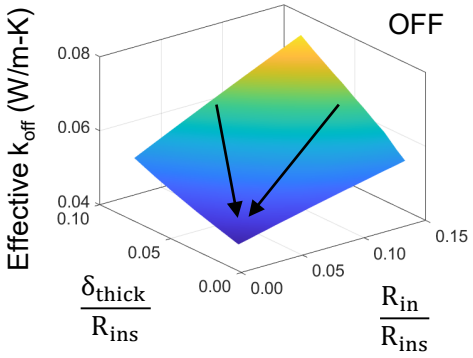
Wax motors

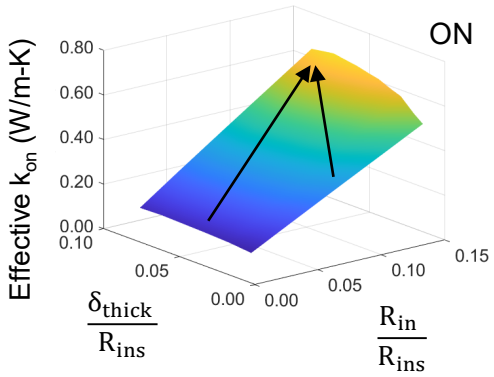
(b) Active control

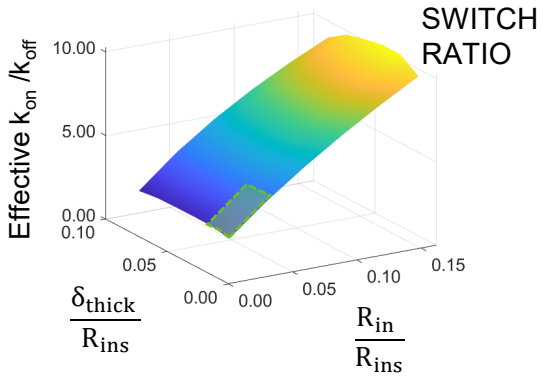


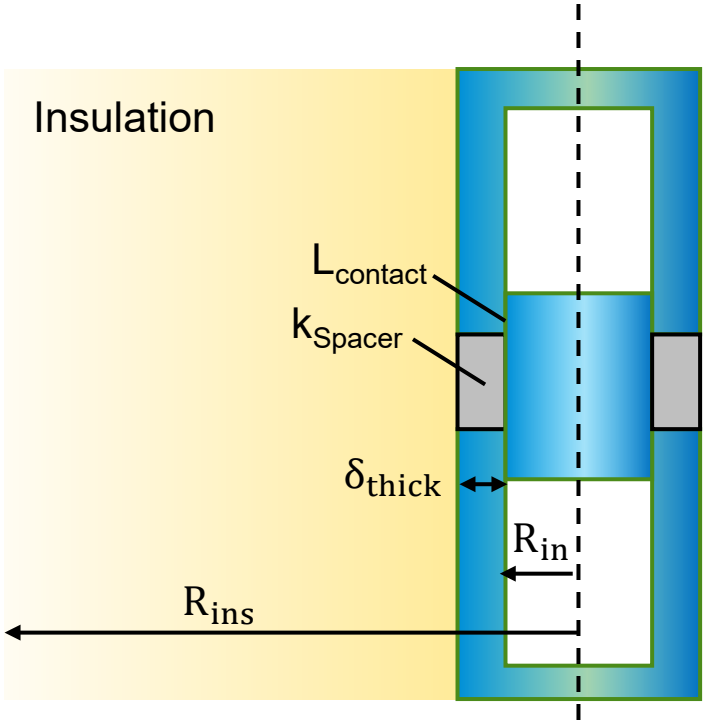
Linear electromagnetic motors
- Electrical power: 5.5 W
- Operation time < 1s
- Energy per event: ~5 J

Performance optimization

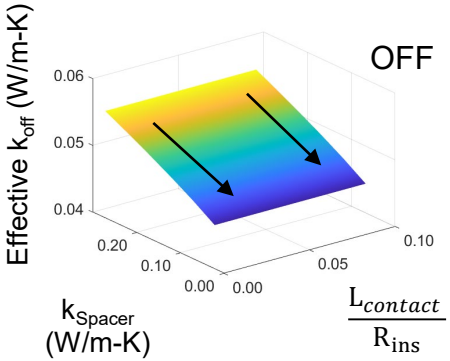


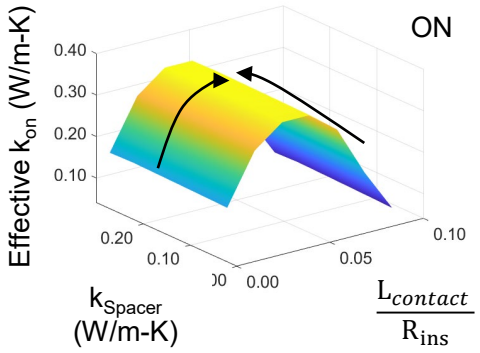


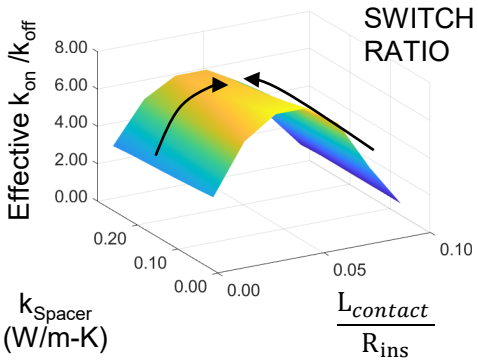


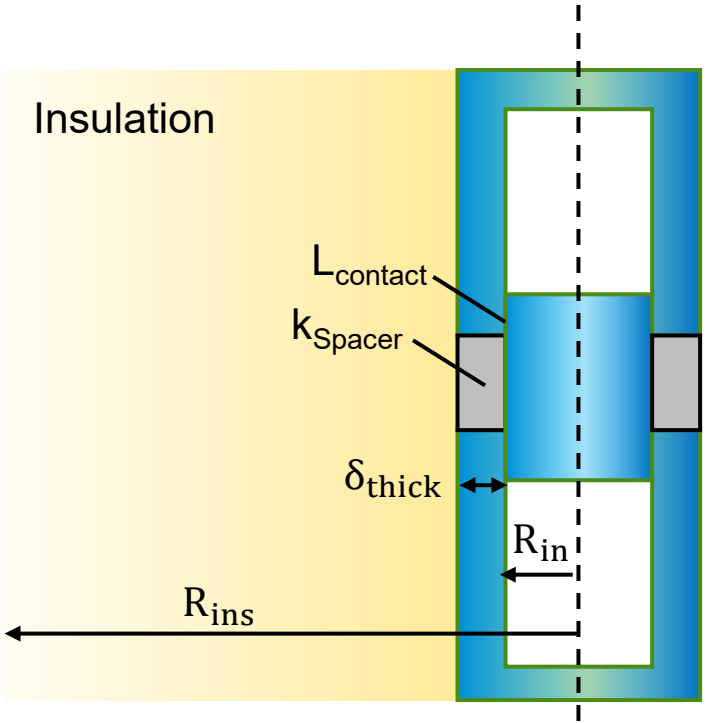


Performance optimization

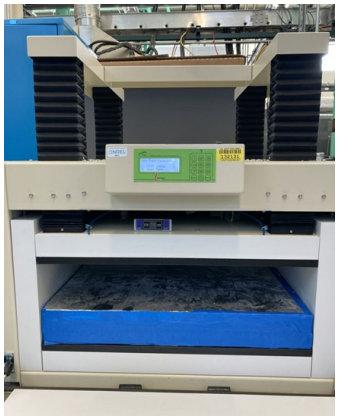


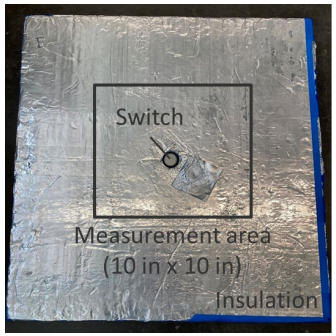


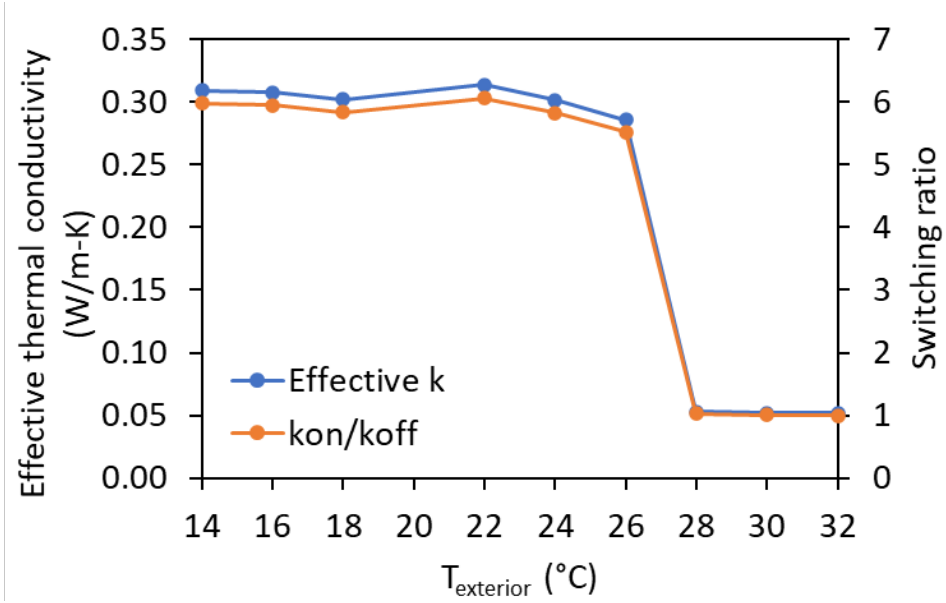




Thermal performance

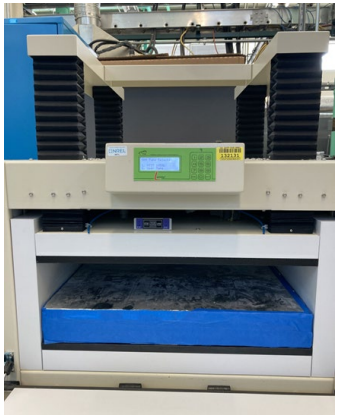


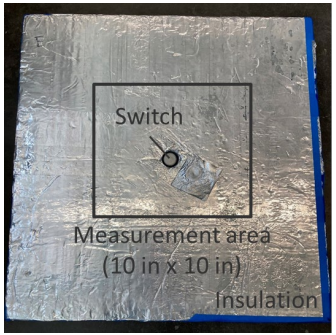


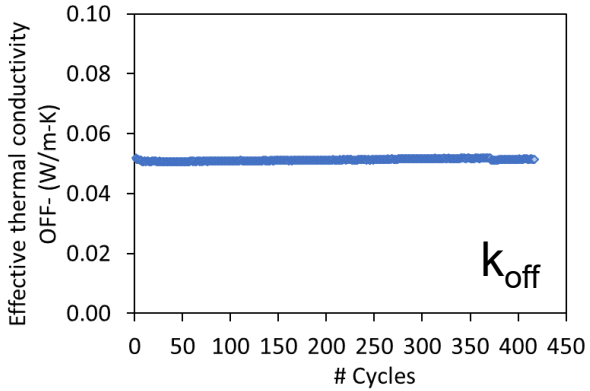


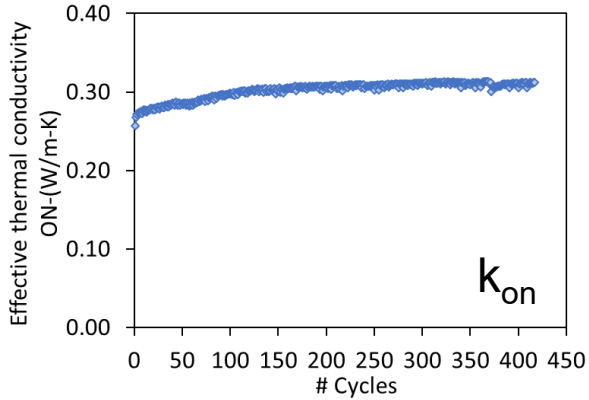
- Measurements performed using HFM FOX600
- 1 thermal switch per 10” x 10” insulation
- Effective $k_{off} \approx 0.051$ W/m·K | Switching ratio $k_{on}/k_{off} \sim 6.0$
- Transition temperature: 26-28 °C

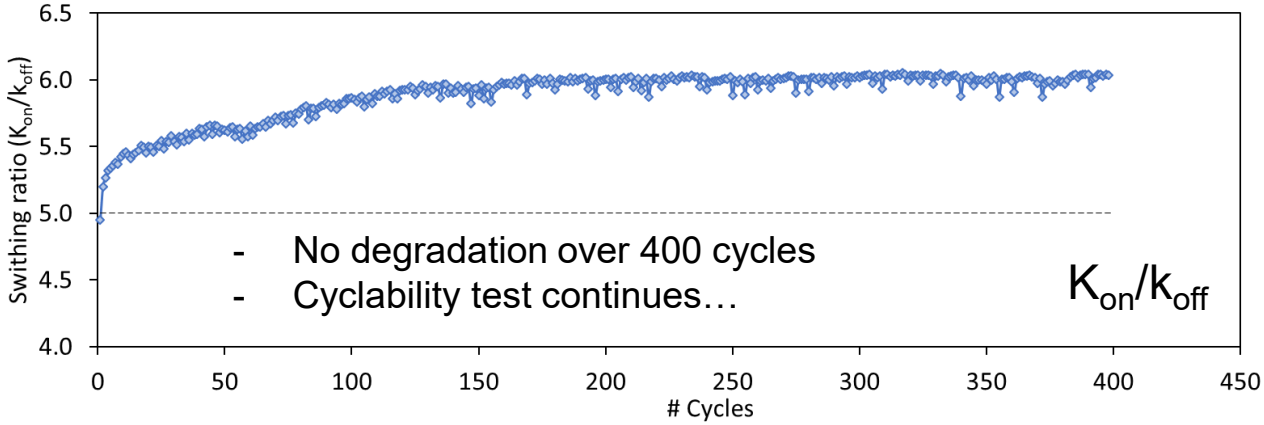
Cyclability test



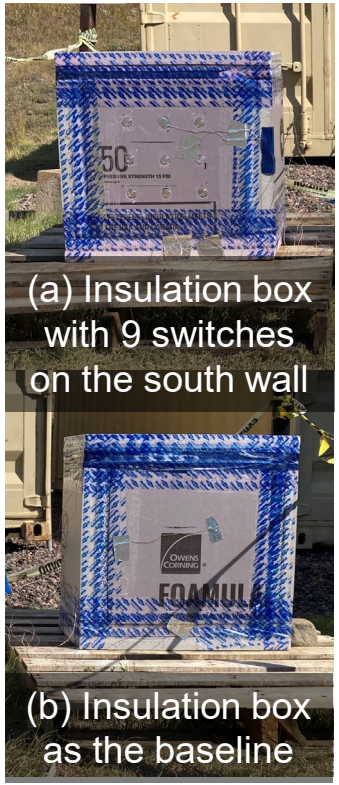


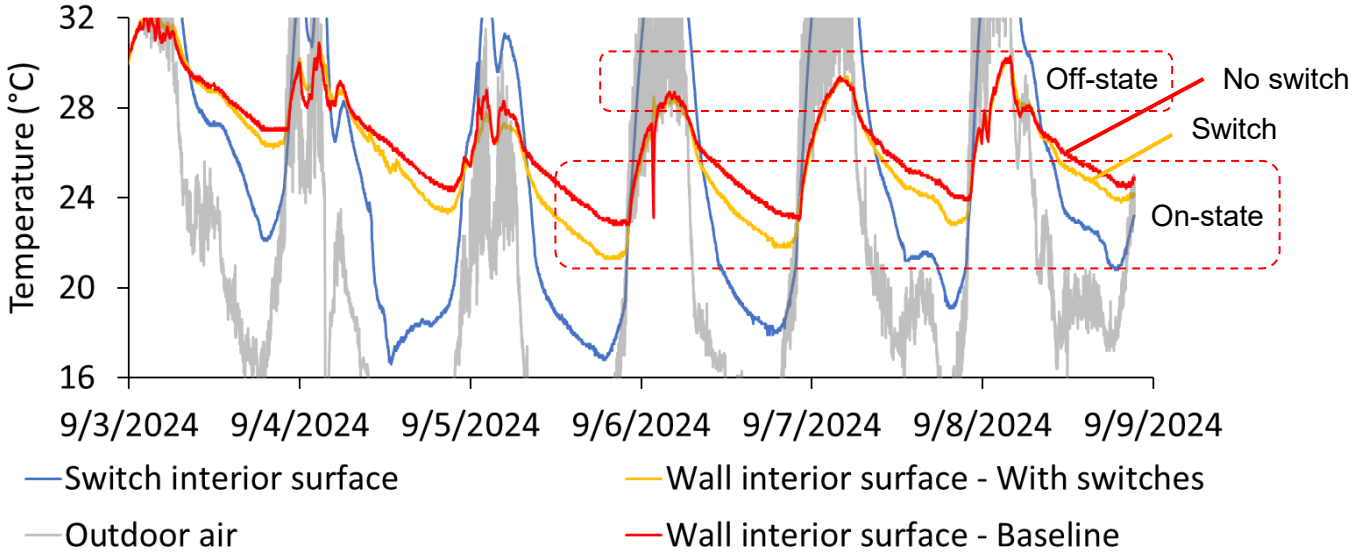






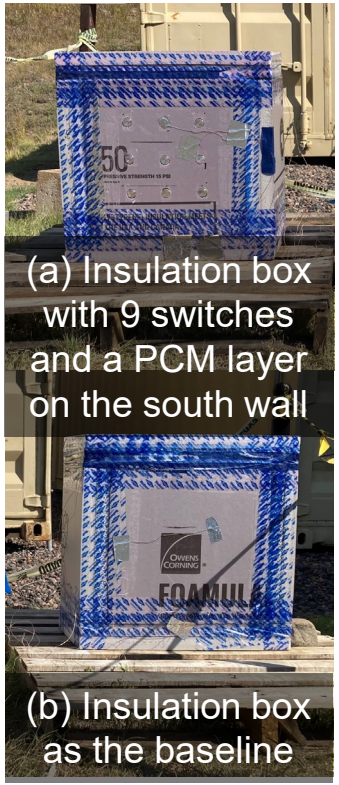
Outdoor test – Thermal switch only

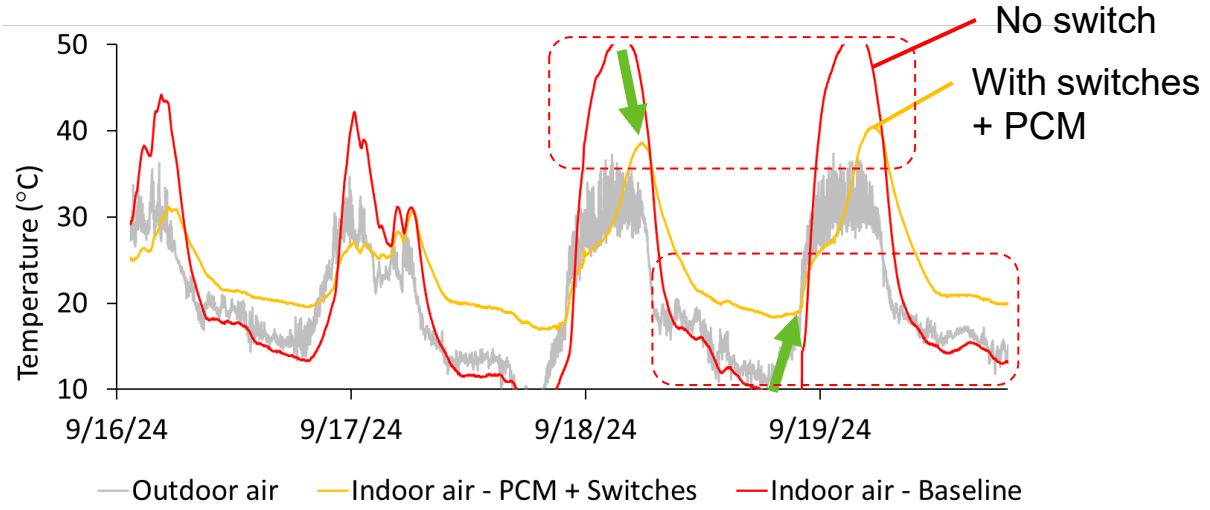




- 4 gallons of water as internal mass in both cases: (a) and (b)
- Climate: Golden CO
- 1-2°C reduction in interior wall surface temperature due to switches

Outdoor test – PCM + Thermal switches





- ~12 mm PCM layer (Rubitherm RT21HC)
- No additional internal thermal mass
- Compared to baseline, PCM + Switches demonstrates:
  - Significant reduction in indoor air temperature fluctuations
  - Enhanced ambient cooling/heating
  - Time lag by up to 2 hours

Key Highlights and Future Work

FY24's key achievements:

- Successfully demonstrated plug-n-play thermal switches
- Effective switch ratio > 5 and $k_{off} \approx 0.051$ W/m·K (1 switch per 100 in^2 insulation)
- No degradation over 400+ cycles
- Significant reduction in indoor temperature fluctuations and lower wall temperature
- Patent: U.S. 12,001,228 B2

FY25 plans and Future work:

- Continued cyclability and durability tests
- 2-step passive/low-power active switches for mixed climates
- Impact on load flexibility and heat resilience
- Scaled-up outdoor tests
- Field test and pilot demonstration
- Technoeconomic analysis

Thank you

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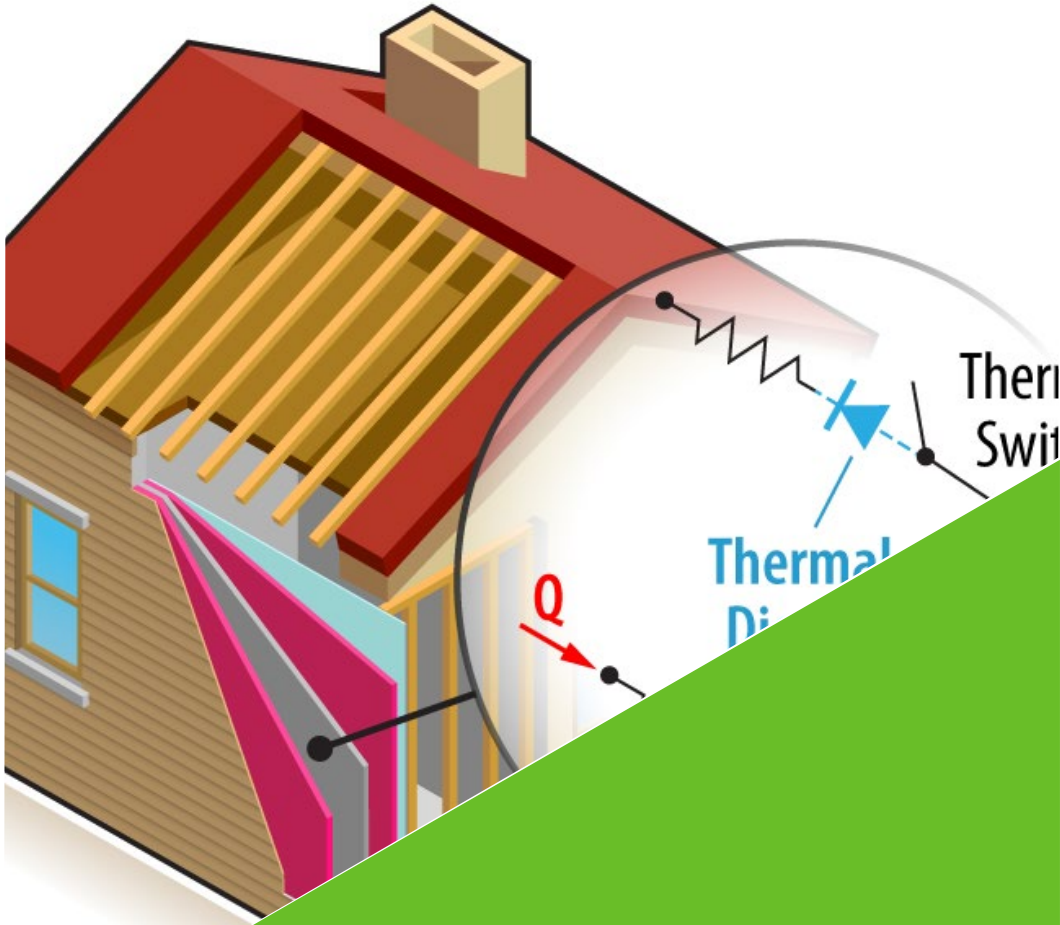

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Reference Slides

Project Execution

	FY2024				FY2025				FY2026			
Planned budget												
Spent budget												
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q1 Milestone: Thermal switch design finalized												
Q2 Milestone: Fabrication, integration, and characterization												
Q3 Milestone: Cyclability tests												
Q4 Milestone: Switch scalability												
Q1 Milestone: PCM + Switch characterization												
Current/Future Work												
Q2 Milestone: Active switches for mixed climates												
Q3 Milestone: Scalability and cyclability tests												
Q4 Milestone: Outdoor and field tests												

- Go/no-go decision points: Switching ratio > 5.0 and k_{off}= 0.05 W/m·K
- Reproduceable performance over 1000 cycles

Team

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Postdoc

Experiments

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Research engineer

Building-scale modeling

Chuck Booten

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Mentor & Supervision