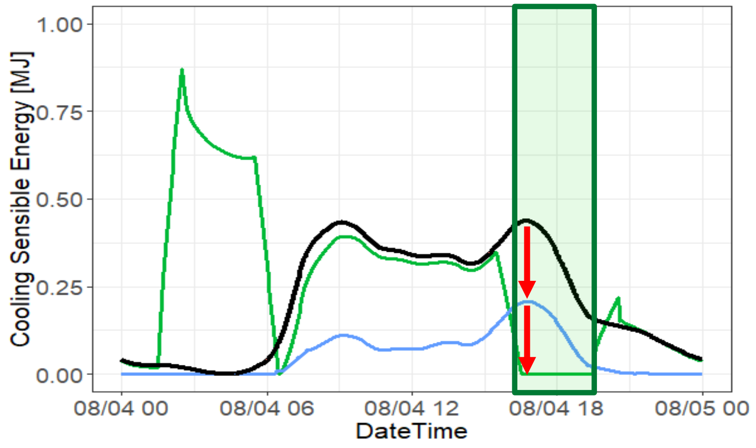
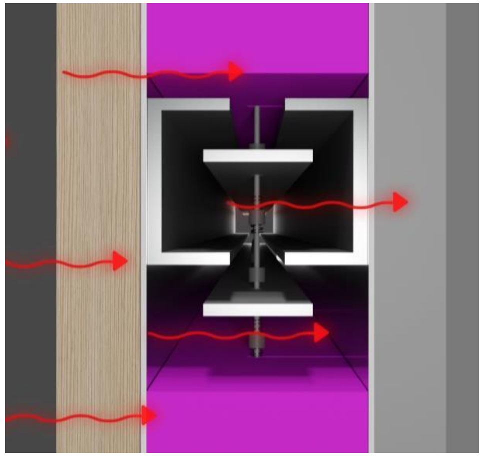
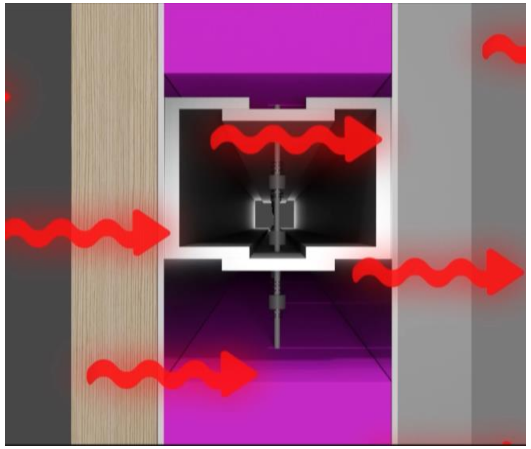
Demonstration of Active Insulation Systems







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WBS 03.01.03.12.27

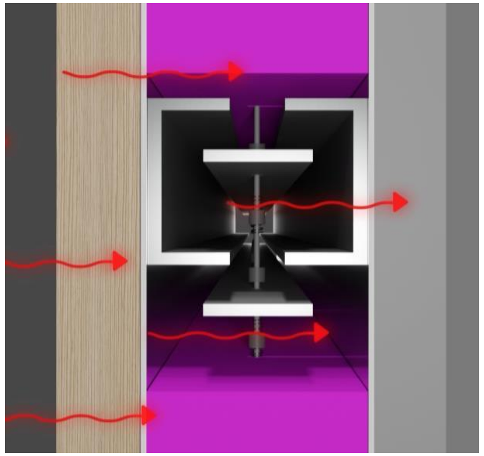
Project Summary

Objectives

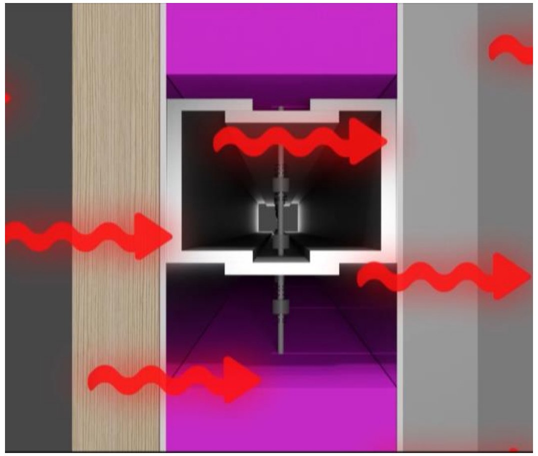
- Develop an AIS prototype
- Demonstrate the benefits of AIS assemblies exposed to natural weather conditions

Outcome

- Validation of predicted performance against physical testing with rule-based and advanced controls
- Demonstrate the feasibility of AIS in actual buildings



R-high



R-low

Team and Partners

Oak Ridge National Laboratory

Building Envelope Materials Research
Grid-Interactive Controls
Integrated Building Deployment and Analysis

Stats

Performance Period: 10/1/2021 – 09/30/2023

DOE budget: $600K, Cost Share: -

Milestone 1: Construction of walls with fully functioning AIS

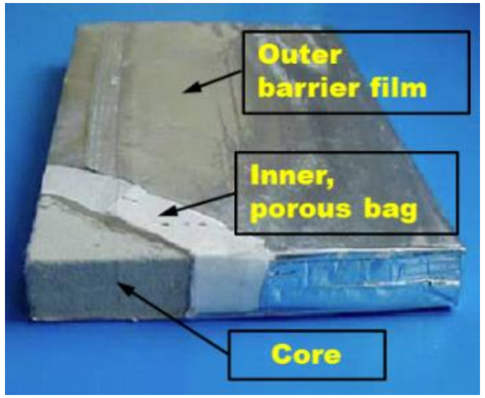
Milestone 2: Energy savings and peak demand of the AIS and baseline walls when exposed to natural weather

Problem

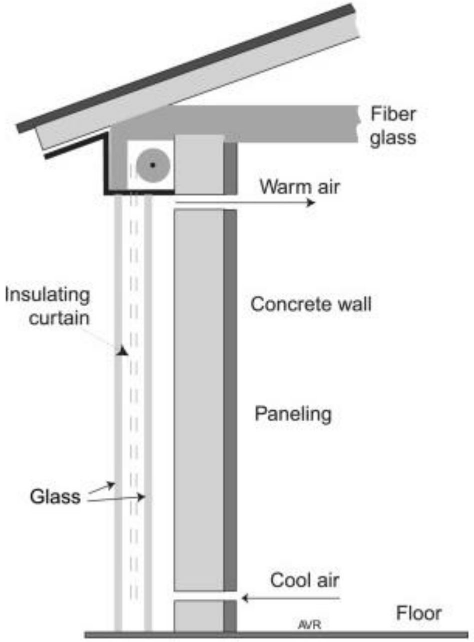
- In 2016, HVAC loads contributed 30% and 38% of the CO_2 emissions in commercial and residential buildings, respectively.
- Increasing insulation levels in building envelopes are bringing diminishing returns.
- Thermal mass in building envelopes is underutilized as a medium for energy storage.
- Passive building envelopes cannot be dynamically optimized to save energy based on indoor and outdoor conditions.
- Active building envelopes can do more than minimize heat loss and gain, effectively turning walls with high thermal mass into a heat pump. However, active envelopes are not currently available.

State-of-the-Art

- Highly insulated Passive Houses
- Most research focuses have been on static high R-value per inch
  - Vacuum insulation panel (VIP)
  - Fiber-reinforced aerogels
  - Durability, high cost, and product availability are challenges for these products
- Applications of PCM (Phase Change Materials)
- Active systems such as Trombe walls are not common
- Active insulation materials and systems have been researched
  - Unpractical, performance lacking



VIP insulation



Trombe wall

Figure credit:
https://www.sciencedirect.com/topics/earth-and-planetary-sciences/trombe-walls

Alignment and Impact

- According to a DOE report[1], the estimated total U.S. technical potential energy savings from active insulation systems is 1.5 quads
- These benefits can further increase by integrating AIS with renewable energy sources to synchronize building energy demand and renewable energy availability
- AIS controlled with battery or solar power can improve resiliency by mitigating extreme indoor conditions during power outages
- Successful AIS demonstration
    - Enables pathway to the adoption of active insulation systems in buildings
    - Provides confidence in energy impact from AIS in real-world
        - Simulations show reductions in HVAC energy consumption by 5% to 70% and peak demand by up to 50%
    - Helps development of a ready-to-install AIS with dynamic insulation and thermal mass components

[1]US DOE (2019)-Grid-interactive Efficient Buildings Technical Report Series: Windows and Opaque Envelope

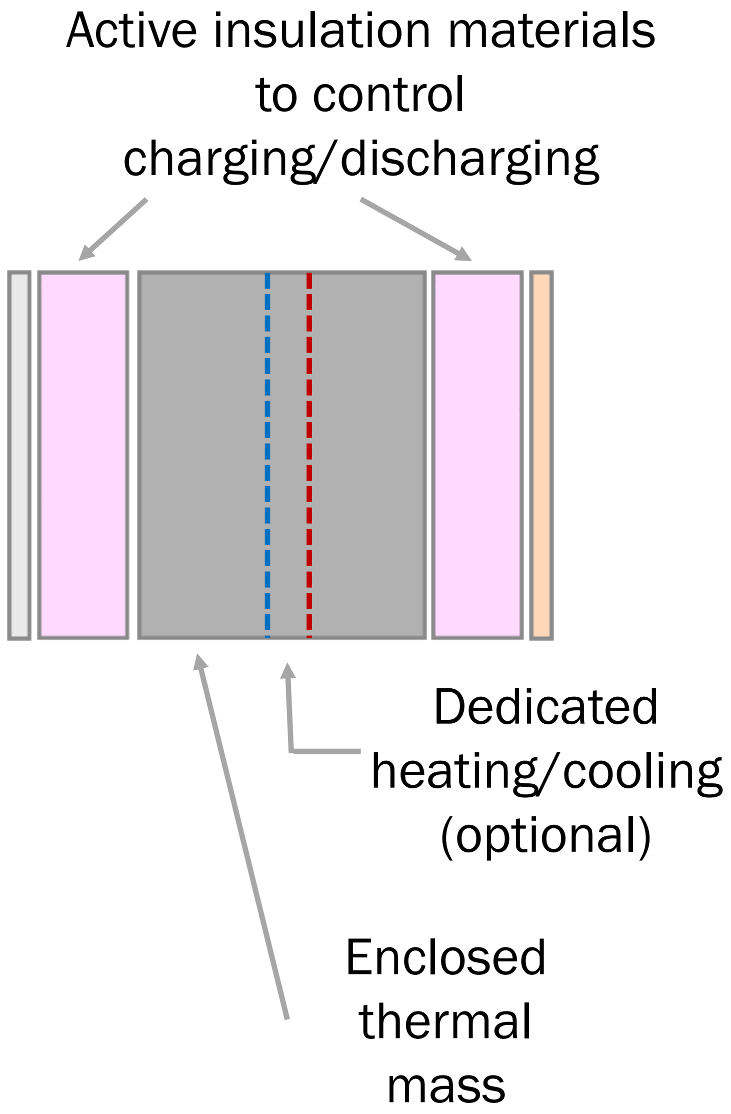
Approach: Active Insulation Material (AIM) and System (AIS)

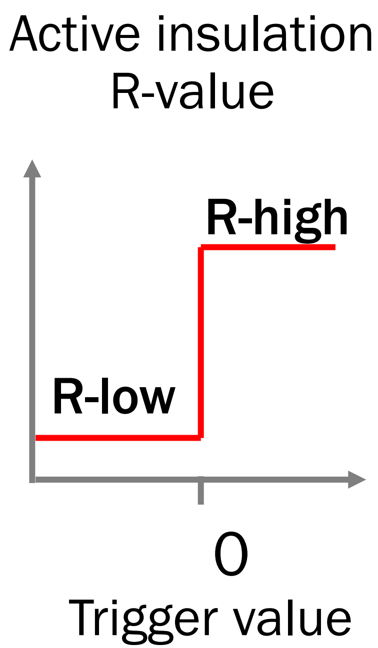
Active Insulation Material:
Material/layer that changes thermal conductivity based on external control

Active Insulation System:
Thermal mass enclosed between active insulation materials

- Thermal mass to enable time shift in energy use and availability
  - Concrete, Phase Change Material
  - Option to integrate dedicated heating/cooling for optimized grid services or use of on-site renewable energy

Goal: Develop a fully functioning AIS and demonstrate its impact on energy savings and peak demand in a real building.





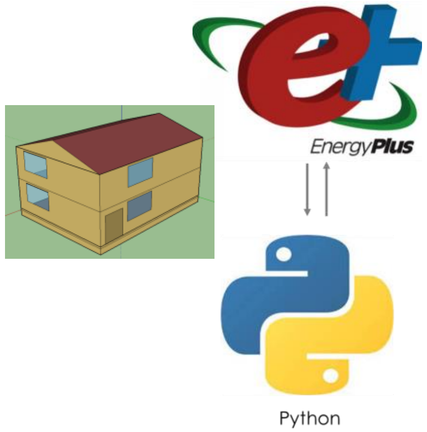
Approach: Major Project Tasks

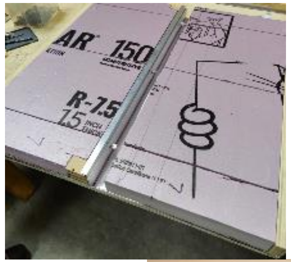
Simulations
- Energy and peak demand
- Control strategies

Prototype Design
- Bench-scale
- Full-scale

Prototype Testing
- Bench-scale
- Full-scale

Field Demonstration
- Test hut construction
- Control systems and instrumentation
- Monitoring
- Evaluation of benefits



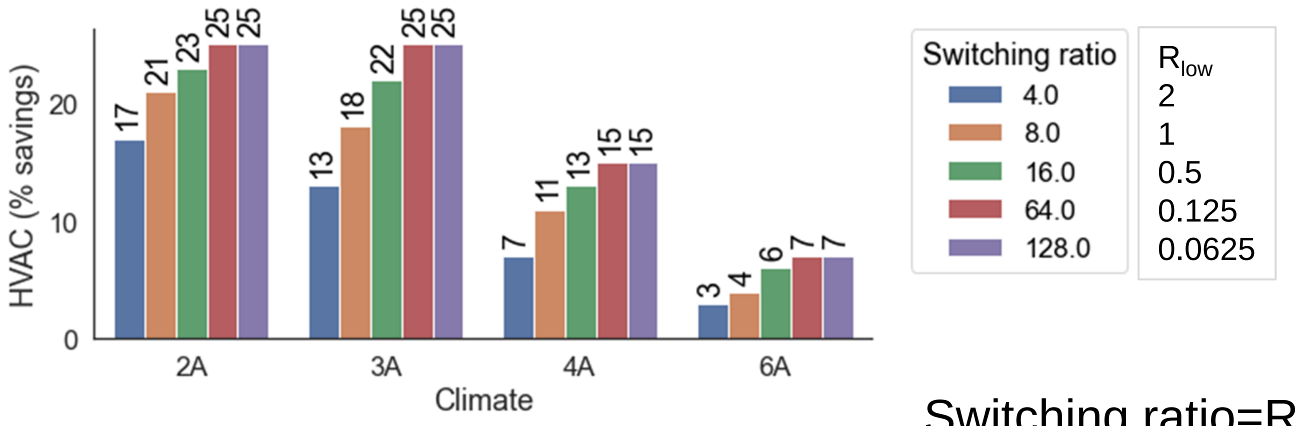


Approach: AIS Selection Criteria and Performance Parameters

Weighted selection criteria:

- Performance
- Cost
- Buildability
- Innovativeness
- Scalability
- Practicality

- R_{high} must be high enough to insulate when stored energy is not available
- R_{low} must be low enough to enable high heat transfer rates to provide heating/cooling



Switching ratio=R_{high}/R_{low}

Key parameters:

Property	Desired criteria
R_{low} R_{high} Thickness	$R_{low} \leq 1$ h·ft²·F/Btu $R_{high} \geq 7$ h·ft²·F/Btu ≤ 2 in
Time to switch states	< 5 min
Actuator	Durable, simple
Efficiency of switching	< 3.4 Btu/ft^2
Cost/ft^2	< \$5/ft^2

Approach: Challenges, Risks, Commercialization, Demonstration

Technical Challenges

- Communication and power supply
  - Centralized wireless sensors
  - Battery operation
- Ease of installation
  - Prefabricated components

Commercialization

- Prefabricated housing
- Component manufacturers

Risks

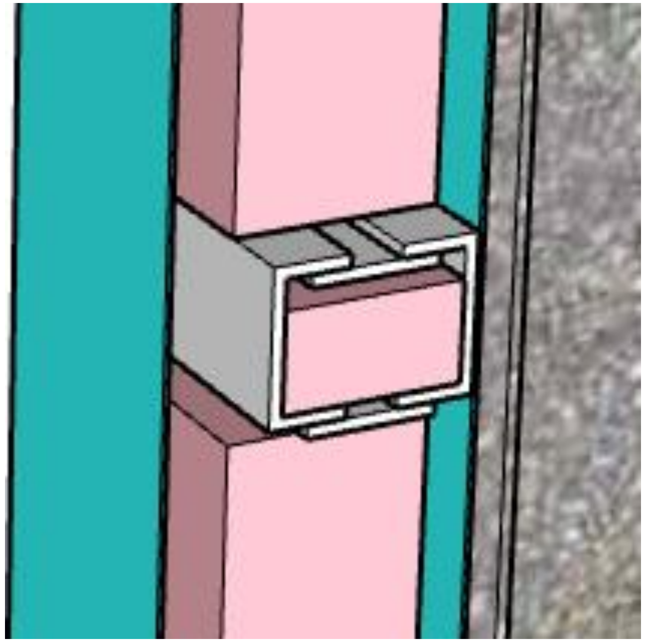
- Failure mode performance
  - Battery-powered performance
- Durability and maintenance
  - Plug-and-play wall components

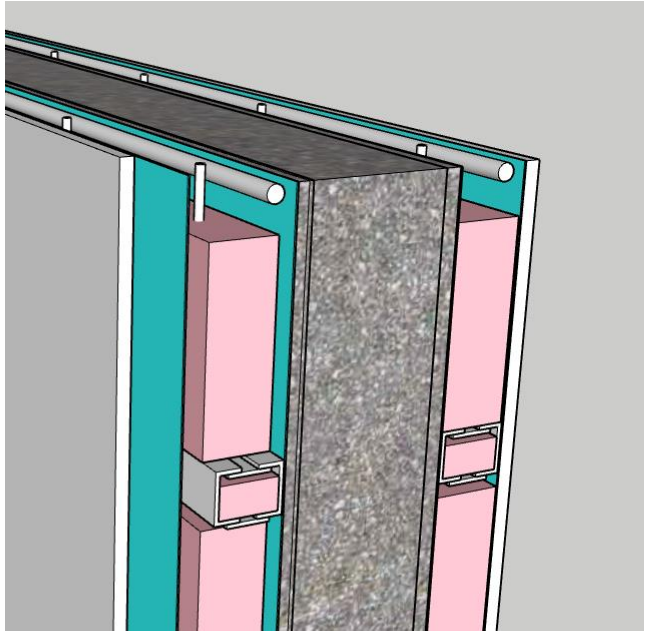
Demonstration

- Testing in natural weather conditions in the test hut walls at NET facility

Progress: AIS Prototype Development

- Design
- Material selections
- Simulated performance predictions vs. Small-scale testing

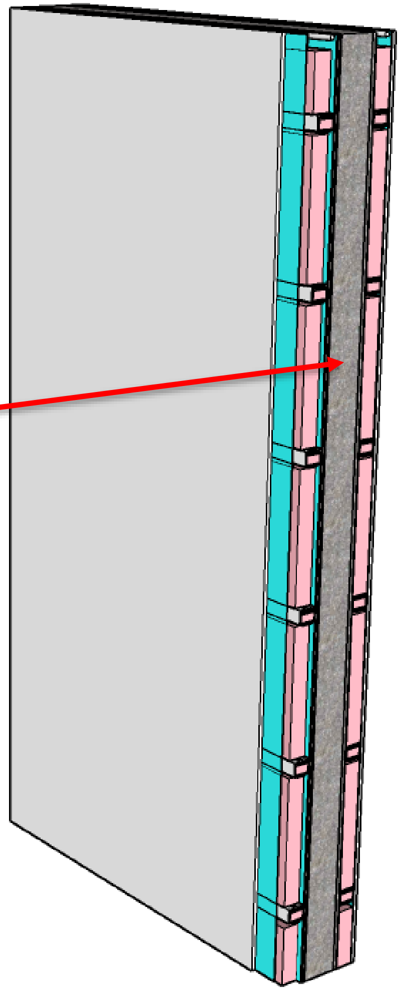




AIS wall with thermal mass

Layers from interior to exterior:

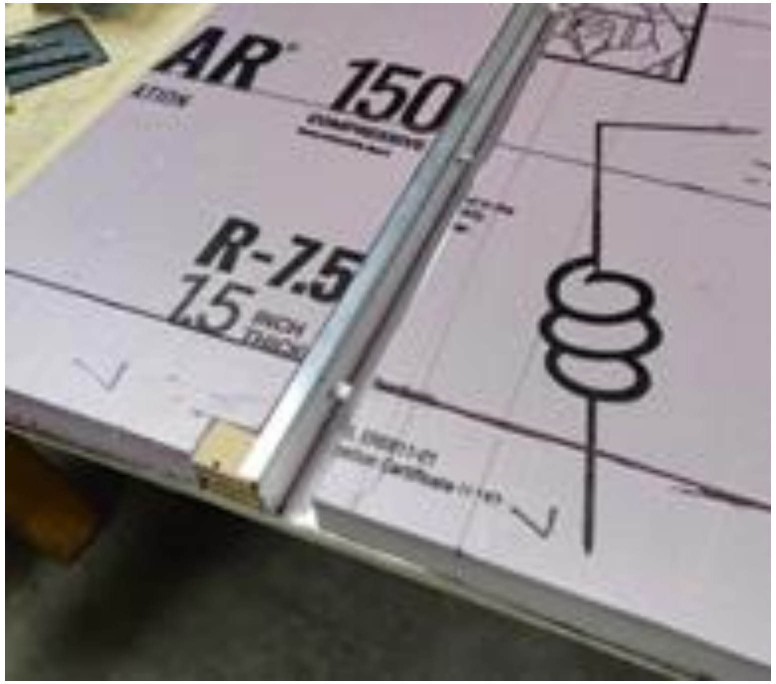
1. Drywall
2. Aluminum foil
3. Insulation with AIS actuators @ 16oc
4. Aluminum foil
5. Thermal mass
6. Aluminum foil
7. Insulation with AIS actuators @ 16oc
8. Aluminum foil
9. Exterior sheathing
10. Cladding



Progress: Bench-Scale Testing and Predicted Performance

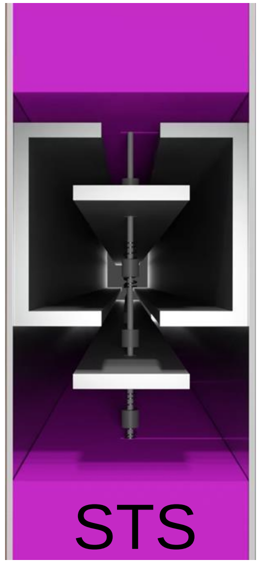
- Insulation and aluminum thicknesses were varied in COMSOL simulations
- 24”x24” Bench-scale prototype was tested using a heat flow meter with multiple heat flux sensors covering the width of the sample
- With 20 mils aluminum foils and 2” rigid foam insulation
  R-high of R-8.2 and R-low R-1.1 was predicted (Switching ratio = Rhigh/Rlow = 7.5)

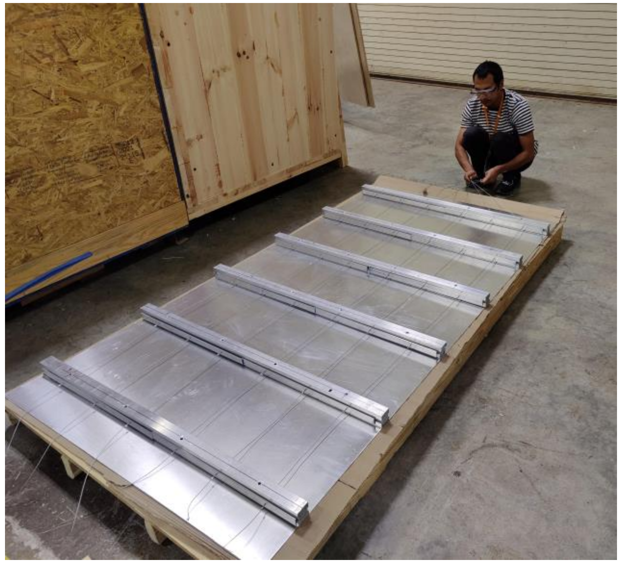
	R-values (°F·ft²·h/Btu)				
Thickness: Insulation Foil	Measured 1”, 10mil	Simulated 1”, 10mil	Simulated 1.5”, 10 mil	Simulated 2", 10 mil	Simulated 2", 20 mil
R-high	4.2	4.3	6.3	8.2	8.2
R-low	1.4	1.3	1.5	1.5	1.1
R-high/R-low	3.0	3.3	4.2	5.5	7.5

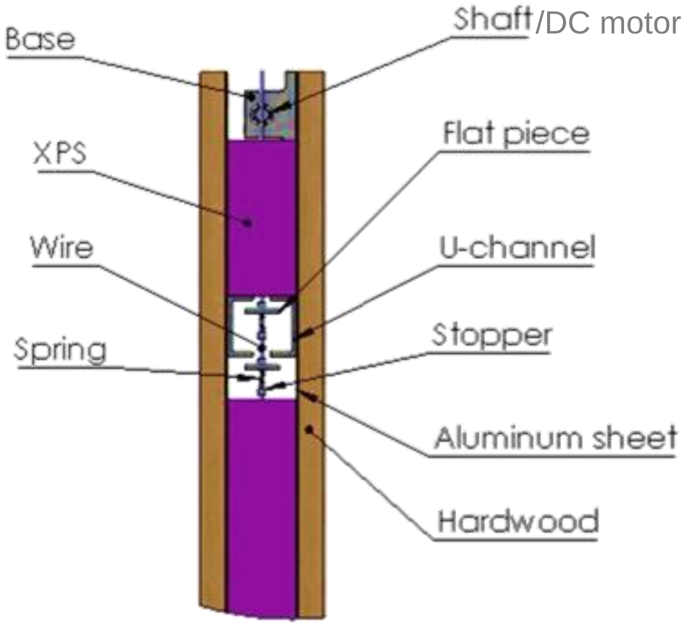


Progress: Full-Scale Prototype Engineering

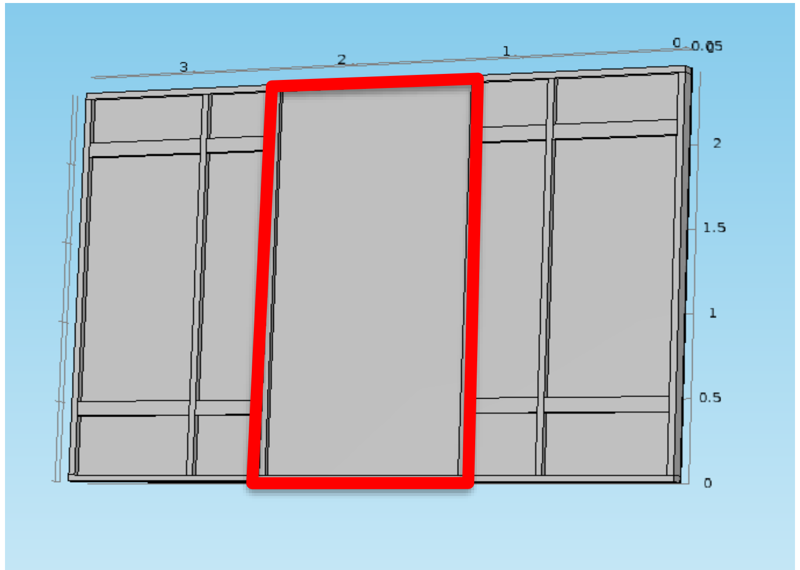
- 6 sections of solid-state thermal switches (STS) per 8' tall wall (16" o.c.)
  - Two aluminum U-channels and flat pieces per STS
- A **dc motor** to control switching
  - Coupled with a **shaft** where the wires are clamped
- **Wires**
  - Coupling all moving parts (flat pieces) together
- **Stoppers**
  - Restrict the movement of flat pieces
- **Springs**
  - Provide tolerance and ensure contact between flat pieces and U-channels
- **Aluminum sheets**
  - Distribute the heat, increasing overall heat flux







Progress: Full-Scale Laboratory Testing



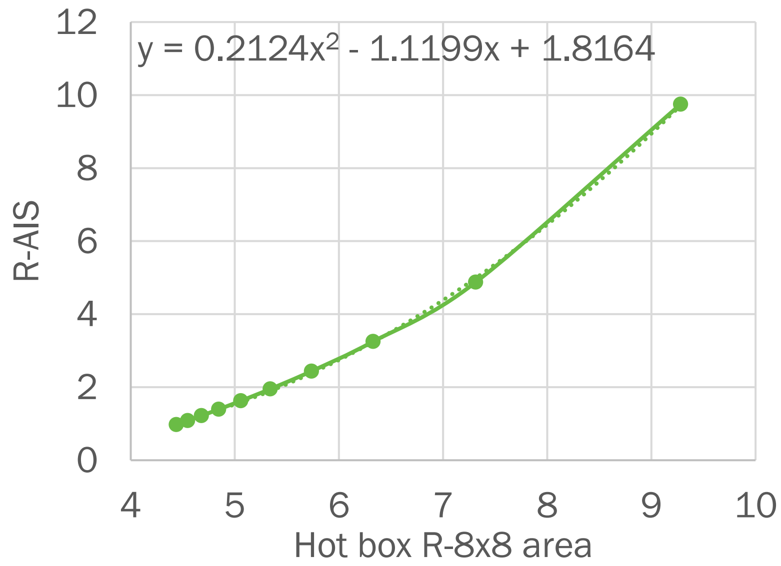
Hot Box Testing with 8'x 8' metering area

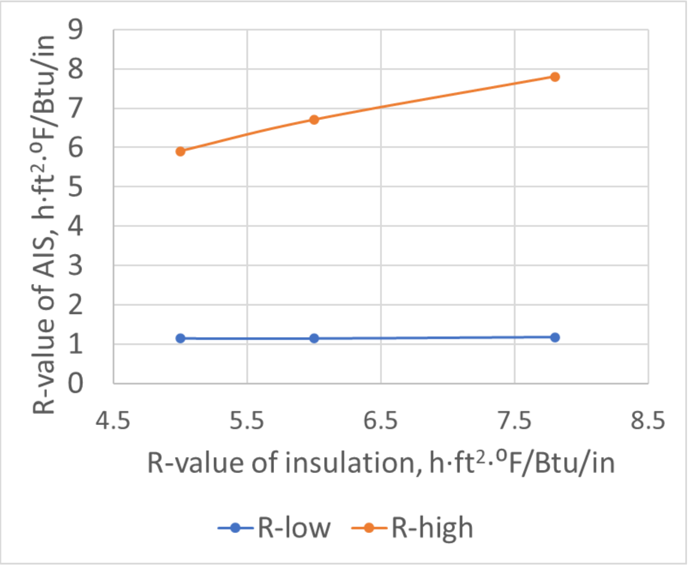
– 4' x 8' Active Insulation Material

– Two 2' x 8' filled with 2" XPS

- AIS R-values derived from Hot Box tests using a validated COMSOL simulation model: R-low=0.98, R-high=5.81

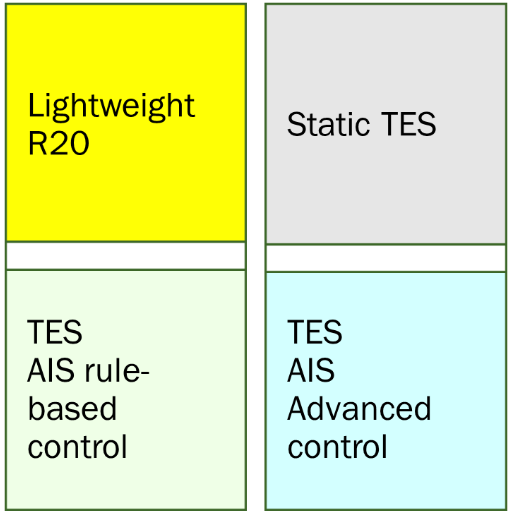
R-high=7 target can be achieved with Polyiso or similar



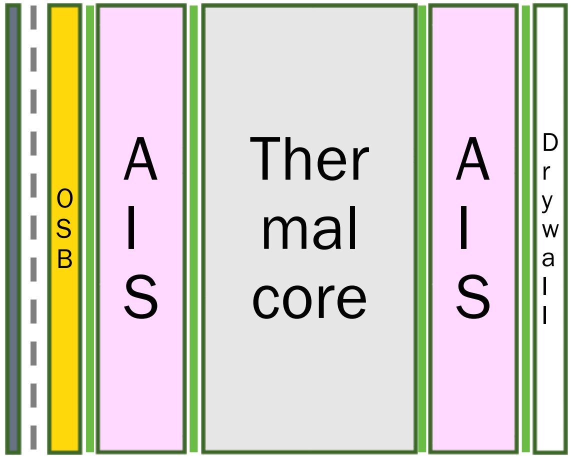


Future Work: Field Monitoring and Data Analysis

- Wall sections (4’x4’)
  - Two Baseline wall designs
    - One with and without thermal mass
  - Two AIS wall designs
    - Rule-based and Advanced-controls wall
- Monitor temperatures and heat fluxes
- Evaluate the benefits of AIS



Wall 1 Wall 2



NET Facility

Test hut in Charleston, SC
Two wall sections are to be converted for testing
Monitoring to start 07/01/2023 for a full year

Future Work: Control Scenarios for Field Testing

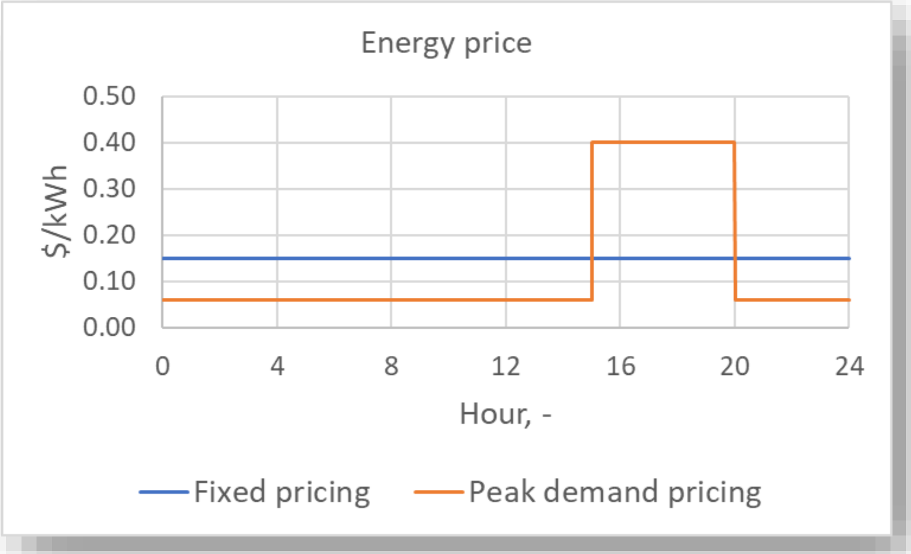
Rule-based control

- Live in the moment without a look to the future
- Maximize free energy storage to thermal mass when available
- Make use of the stored energy to provide heating/cooling to the test hut whenever possible

Advanced control

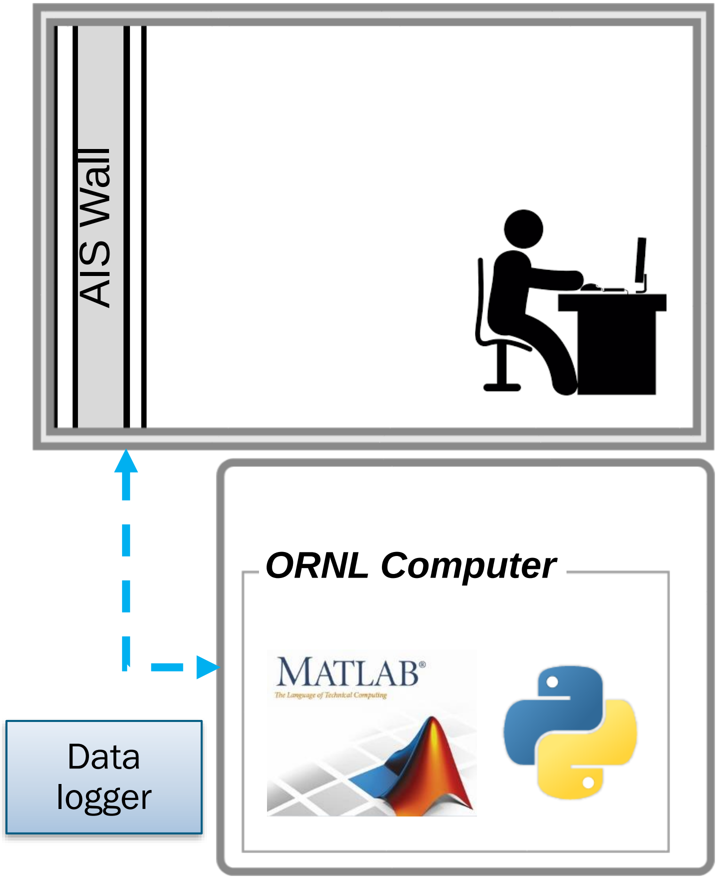
- Cost profile for energy use during peak and off-peak hours
- Weather forecast for a few hours ahead
- Predict optimal control strategy to minimize cost, energy use, or peak demand

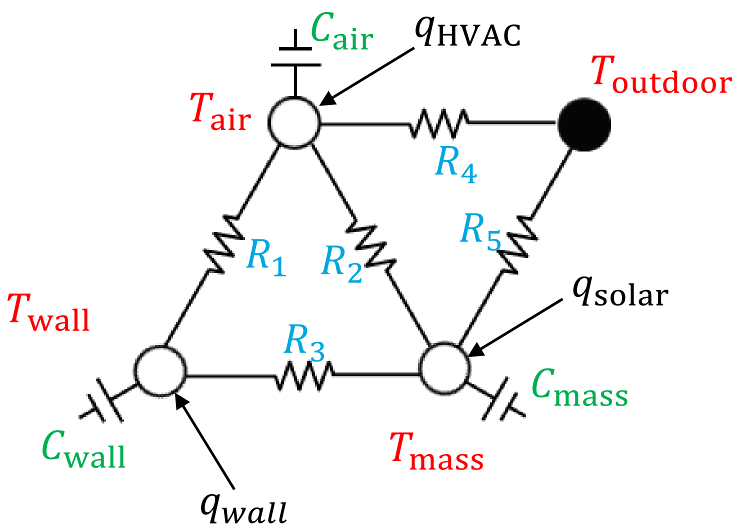
Example: Summer pricing for electricity



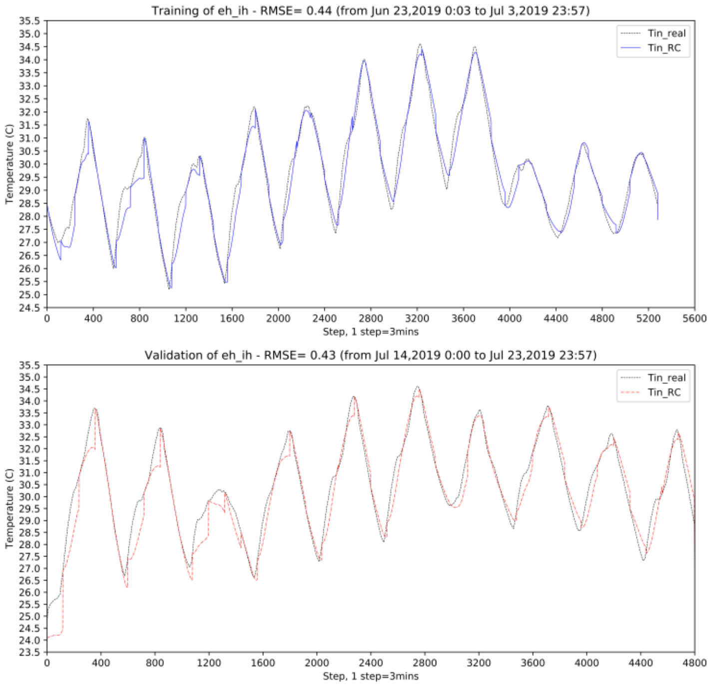
Future Work: MPC Design and Deployment

- Control-oriented data-driven building and system models
- Onsite data collection for the modeling (temperature sensors, heating/cooling)
- Remote activation through communication API





$$q_{HVAC} = f_1(T_{air}, T_{VAV}, Q_{VAV})$$



Publications and Intellectual Property

- Journal and conference papers:
  1. Iffa, E., Hun, D., Salonvaara, M., Shrestha, S., & Lapsa, M. (2022). Performance evaluation of a dynamic wall integrated with active insulation and thermal energy storage systems. Journal of Energy Storage, 46, 103815.
  2. Sungkyun Jung, Yeobeom Yoon, Piljae Im, Mikael Salonvaara, Jin Dong, Borui Cui, Melissa Lapsa, Peak cooling load shift capability of a thermal energy storage system integrated with an active insulation system in US climate zones, Energy and Buildings, Volume 277, 2022, 112484, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2022.112484.
  3. Iffa, E., Salonvaara, M., Kunwar, N., Shrestha, S., Boudreaux, P., Hun, D., Development and Performance Evaluation of an Active Insulation System Wall. Buildings XV Conference, 2022.
  4. Cui B, Dong J, Lee S, Im P, Salonvaara M, Hun D, Shrestha S. Model predictive control for active insulation in building envelopes. 2022. Energy and Buildings 267:15, 112108. https://doi.org/10.1016/j.enbuild.2022.112108
  5. Atkins C, Hun DE, Im P, Post B, Slattery B, Iffa E, Cui B, Dong J, Barnes A, Vaughan J, Roschli A, Salonvaara M, Shrestha S, Jung S, Chesser P, Heineman J, Wang P, Jackson A, Lapsa M. 2022. Empower Wall: Active insulation system leveraging additive manufacturing and model predictive control. Energy Conversion and Management 266, 115823. https://doi.org/10.1016/j.enconman.2022.115823
  6. Iffa, E., Salonvaara, M., & Hun, D. (2021, November). Energy performance analysis of smart wall system with switchable insulation and thermal storage capacity. In *Journal of Physics: Conference Series* (Vol. 2069, No. 1, p. 012092). IOP Publishing.
  7. Kunwar, N., Salonvaara, M., Iffa, E., Shrestha, S., Hun, D., Performance assessment of active insulation systems in residential buildings for energy savings and peak demand reduction. Submitted to Applied Energy.
- Provisional patent application 63/429238
  – “Solid-State Thermal Switch Panel for Thermal Storage” by Som Shrestha, Mikael Salonvaara, Emishaw Iffa, Niraj Kunwar, Diana Hun, Philip Boudreaux, and Tianli Feng

Thank you

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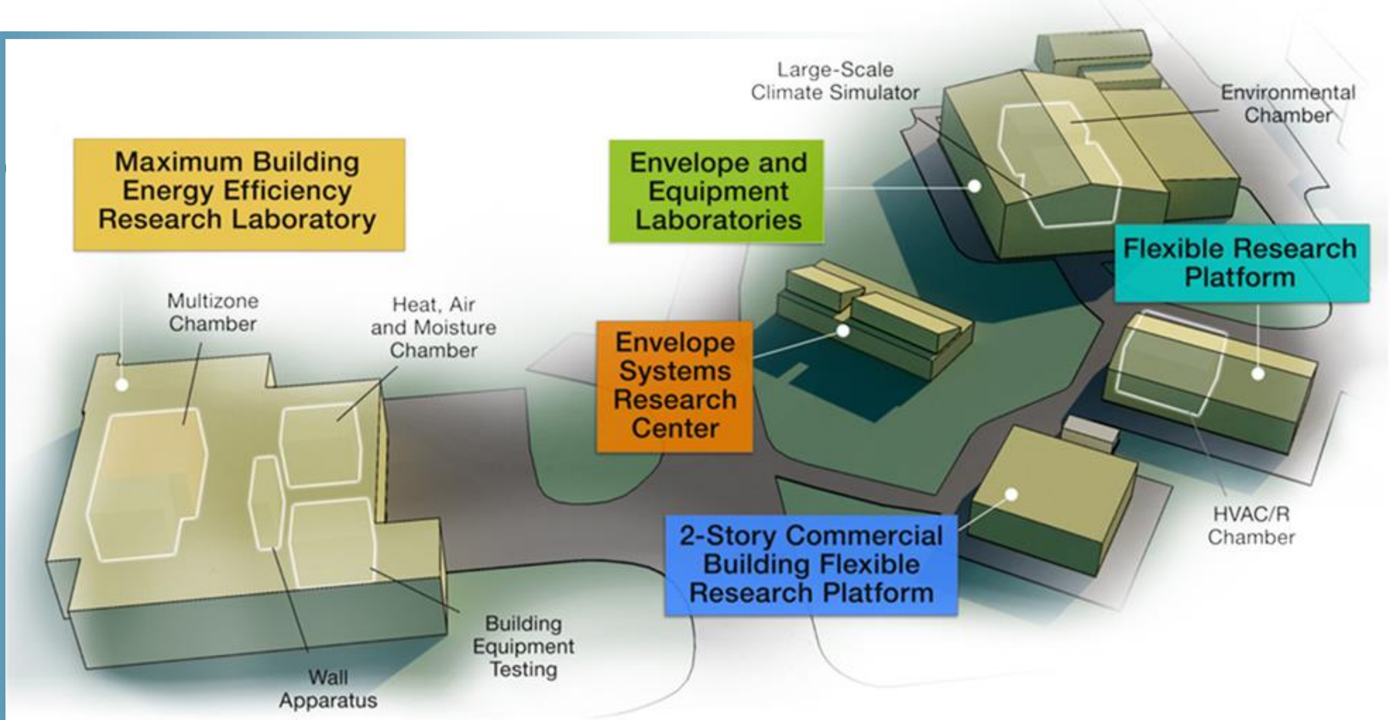

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Scientific and Economic Results

238 publications in FY20
125 industry partners
27 university partners
10 R&D 100 awards
42 active CRADAs

BTRIC is a DOE-Designated National User Facility

REFERENCE SLIDES

Project Execution

	FY2022				FY2023				FY20ZZ			
Planned budget	$440K				$300K							
Spent budget	$375K				$75K							
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
M1: Completed full-scale AIS wall design												
M2: Procurement of materials												
M3: AIS constructed with actuator, trigger and controls												
M4: Construction of typical wall and two AIS walls in test hut												
Current/Future Work												
M5: First quarter field test results analyzed and controls refined.												
M6: Second quarter field test results: Energy savings and peak demand reduction evaluated and compared to baseline.												
M7: Final report.												

Team

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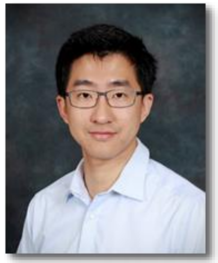

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System Design and Assembly

Advanced Controls