Active Insulation Systems

Scenario 2
(Reduce Energy Use)
In-out coupling

Scenario 3
(Reduce Peak Loads)
Precondition

Scenario 4a
(Reduce Energy Use)
Double control

Oak Ridge National Laboratory
Florian Antretter
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Project Summary

Timeline:
Start date: October 1, 2018
Planned end date: September 30, 2019

Key Milestones:
1. Determined simulation procedure, December 31
2. Summarized simulation results, June 30
3. Developed schematic designs for two active insulation systems (AISs), September 30

Key Partners:
The project is an initial scoping study.
After confirmation that active insulation achieves significant energy savings, potential partners for the highest impact solutions will be identified in a targeted manner.

Budget:
Total Project $ to Date:
- DOE: $240K
- Cost share: $0K

Total Project $:
- DOE: $350K
- Cost share: $0K

Project Outcome:
Simulation results will indicate whether AISs are a technology that should be pursued to make building envelopes dynamic based on:
- Potential energy savings
- Potential reductions in peak demand
Challenge

• Current opaque envelopes are static systems in dynamic environments that cannot do the following:
  – Use beneficial outdoor conditions
  – Use dynamic controls
  – Control and optimize heat storage
    • Preconditioning
    • Integrate renewable sources

• Building envelope storage capacity is being underused
  – Single family wood-frame building storage capacity ~11 kWh/K
    (Diurnal use ~30 kWh, Mass Walls ~25 kWh/K, Powerwall II: 13.5 kWh)
  – Single family water heater storage capacity ~0.22 kWh/K

• AISs
  – Can they save energy and provide grid services?
AIS: Material/system that changes thermal conductivity based on external control

Approach and Team

Review
- State-of-the-art review
  - Select tool
  - Select setup

Screening simulations
- Screening study
  - Select high-impact cases

In-depth
- Iterative refinement
- Optimization study
  - Select design-phase cases

Design
- Schematic designs
  - 12/19

- Philip Boudreaux, PhD
  - Envelope Systems, Modeling

- Som Shrestha, PhD
  - EnergyPlus Modeling

- Florian Antretter
  - Dynamic Building Performance

- Borui Cui, PhD
  - Optimization Algorithms

- Diana Hun, PhD
  - Envelope Systems New Materials

- Mikael Salonvaara
  - Grid Impact

- 12/18
- 03/19
- 06/19
# Systems and Technologies

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Description</th>
<th>Reference</th>
<th>Conductivity</th>
<th>Speed of change</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
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<tr>
<td><strong>Gas Pressure</strong></td>
<td>Variable conductance insulation</td>
<td>Benson (1994)</td>
<td>0.025</td>
<td>0.200</td>
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<td></td>
<td>Hydrogen adsorption/desorption</td>
<td>Horn (2003)</td>
<td>0.003</td>
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<td></td>
<td>Variable pressure aerogel blanket</td>
<td>Berge (2015)</td>
<td>0.011</td>
<td>0.017</td>
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<tr>
<td></td>
<td>Variable pressure fumed silica VIP</td>
<td>Berge (2015)</td>
<td>0.007</td>
<td>0.019</td>
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<tr>
<td><strong>Convection (liquid)</strong></td>
<td>Fluid tanks with different conductivity</td>
<td>Al-Nimr (2009)</td>
<td>0.018</td>
<td>0.640</td>
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<td></td>
<td>Permeodynamic wall (breathing wall)</td>
<td>Imbabi (2006)</td>
<td>0.002</td>
<td>0.039</td>
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<td></td>
<td>Parietodynamic wall (dynamic void space)</td>
<td>Imbabi (2012)</td>
<td>0.036</td>
<td>0.130</td>
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<td><strong>Convection (air)</strong></td>
<td>Translucent element with insulation panel between two air gaps</td>
<td>Pflug (2015, 2012)</td>
<td>0.046</td>
<td>0.170</td>
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<td>Porous wall with cross airflow</td>
<td>Ascione (2015)</td>
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<td>Forced airflow through insulation layer</td>
<td>Elsarrag (2006, 2009, 2012)</td>
<td>0.014</td>
<td>0.090</td>
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<td><strong>Multi-layer</strong></td>
<td>Collapsing number of air layers</td>
<td>Kimber (2014)</td>
<td>0.026</td>
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<td>Transparent exterior with movable multilayers</td>
<td>Pflug (2017)</td>
<td>0.013</td>
<td>0.262</td>
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<td><strong>Thermodiode</strong></td>
<td>Direction of nanotube</td>
<td>Wu (2014)</td>
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<td>1.200</td>
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<td></td>
<td>Bidirectional thermodiode</td>
<td>Varga (2002)</td>
<td>0.061</td>
<td>0.360</td>
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</table>

Most promising technologies provide **controllable thermal conductivity in a broad range with fast switching**
## Modeling and Control

<table>
<thead>
<tr>
<th>Tool</th>
<th>Approach</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESP-r</td>
<td>Source code modifications</td>
<td>Loonen et al. (2014)</td>
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<tr>
<td>TRNSYS</td>
<td>No detailed description about implementation</td>
<td>Pflug et al. (2015)</td>
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<td>TES</td>
<td>Air channels to short circuit insulation</td>
<td>Elsarrag et al. (2012)</td>
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<td></td>
<td>• “Surface Control: Movable Insulation”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Energy Management System</td>
<td></td>
</tr>
</tbody>
</table>

Loonen et al. (2014):

“Despite the **limitations in existing software tools**, researchers and engineers have developed numerous customized simulation strategies for predicting the performance of responsive building elements in whole-building performance simulation programs... So far, most of these attempts have used **workarounds, which tend to rely on approximations or simplifications.**”
Research Gaps

- **Proposed technologies**
  - Only tested at lab level or with bench-scale prototypes
  - Most have high energy demand to change thermal conductivity
  - Focus on exterior walls
  - Do not address building integration

- **Control strategies are very simple or too complex**

- **No coupling with dedicated heat charging/discharging system**
  - Hydronic system
  - Direct electric heat

- **No reproducible and easy-to-implement simulation methods**
# Application Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Envelope assembly</th>
<th>Assembly and monitors</th>
<th>Control Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AIS$_{ext}$ + low thermal mass</td>
<td><img src="image1" alt="Image" /></td>
<td>Control: Difference in surface temperature Lightweight indoor-outdoor coupling</td>
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<tr>
<td>2</td>
<td>AIS$_{ext}$ + high thermal mass</td>
<td><img src="image2" alt="Image" /></td>
<td>Control: Difference in surface temperature Mass indoor-outdoor coupling</td>
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<tr>
<td>3</td>
<td>Exterior static insulation + high thermal mass + AIS$_{int}$</td>
<td><img src="image3" alt="Image" /></td>
<td>Control: Difference in surface to zone temperature, time of day Pre-conditioning with HVAC (Peak Reduction)</td>
</tr>
<tr>
<td>4</td>
<td>AIS$<em>{ext}$ + high thermal mass + AIS$</em>{int}$</td>
<td><img src="image4" alt="Image" /></td>
<td>Control: Difference surfaces to thermal mass temperature, difference surface to zone (a) free energy, (b) additional pre-conditioning</td>
</tr>
<tr>
<td>5</td>
<td>AIS$<em>{ext}$ + high thermal mass + dedicated heating/cooling + AIS$</em>{int}$</td>
<td><img src="image5" alt="Image" /></td>
<td>Control: Difference surfaces to thermal mass temperature, time of day energy price Total control over charging and discharging time with highest localized comfort control</td>
</tr>
</tbody>
</table>

- Energy Price
- Exterior surface
- Thermal mass
- Interior surface
- Zone operative temperatures
- Active Insulation
- Static Insulation
- No Insulation
- Cladding
- Drywall
- Low Mass
- High Mass
Modeling in Energy Plus

DOE Prototype Buildings:
- Residential
- Medium office
- Stand-alone retail

Actuators: Building components with active insulation

Sensors: Triggering parameters:
- Temperatures
  - Surfaces
  - Mass
  - Operative
- Surface heat fluxes
- Energy price

Energy Plus Energy Management System
Control: User-defined, rule-based control algorithm

Temperature Difference in-out [°C]
Simulation Study Outline

**Screening Simulation Matrix**

<table>
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<tr>
<th></th>
<th>Base light</th>
<th>Base mass</th>
<th>Scen 1</th>
<th>Scen 2</th>
<th>Scen 3</th>
<th>Scen 4a</th>
<th>Scen 4b</th>
<th>Scen 5</th>
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<tr>
<td>Residential</td>
<td>CZ 1</td>
<td>CZ 2</td>
<td>CZ 3</td>
<td>CZ 4</td>
<td>CZ 5</td>
<td>CZ 6</td>
<td>CZ 7</td>
<td>CZ 8</td>
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<tr>
<td>Medium Office</td>
<td>CZ 1</td>
<td>CZ 2</td>
<td>CZ 3</td>
<td>CZ 4</td>
<td>CZ 5</td>
<td>CZ 6</td>
<td>CZ 7</td>
<td>CZ 8</td>
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<tr>
<td>Stand-alone Retail</td>
<td>CZ 1</td>
<td>CZ 2</td>
<td>CZ 3</td>
<td>CZ 4</td>
<td>CZ 5</td>
<td>CZ 6</td>
<td>CZ 7</td>
<td>CZ 8</td>
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</tbody>
</table>

Matrix with
- 48 Baseline variants
- 144 Scenario variants

**Iterative Refinement**

Identify options with potential based on
- Energy demand
- Peak load

Improve iteratively

Identify ~4 ideal combinations

**Optimization Simulation**

\[
f = \min \sum_{t=0}^{t=24} Energy_{cooling+heating}
\]

\[
f = \min \left( \sum_{t=start}^{t=end} PeakLoad_{cooling} + \sum_{t=start}^{t=end} PeakLoad_{heating} \right)
\]

Apply evolutionary algorithm in conjunction with multi-objective optimization functions
Example Results: Residential Summer

Temperature of mass fluctuates around set point

- Precondition and discharge of mass
- Natural cooling
- Natural cooling + controlled discharge

Los Angeles Residential Prototype
South Wall - August 4

- Wall as naturally driven cooling element (Scenario 2, 4a)
- Coast through peak hours (Scenario 3)
Impact - Energy Savings

Scenario 2
(Reduce Energy Use)
In-out coupling

Scenario 3
(Reduce Peak Loads)
Precondition

Scenario 4a
(Reduce Energy Use)
Double control

Total change in kBtu
Grid Challenge: Afternoon Ramp

- Shift cooling demand away from “ramp” using active loading
- Lower consumer cost due to Time Of Use price

Building contribution to address grid challenges: Increase efficiency and shed/shift load

Residential Prototype Building
Los Angeles
Stakeholder Engagement

• Presentation at the ASHRAE 2019 Buildings XIV International Conference
• Ongoing discussions with other national labs on ongoing simulation efforts on thermal storage

FY20 and Beyond (DOE funds approved only for FY19):
Based on impact and requirements:
• Involve industry to develop materials and systems
• Involve industry to include controllable building envelopes in building energy management systems
• Discussions with utilities on load shedding, shifting, and modulation requirements
Remaining Work and Outlook

Remaining FY19 Work:

• Simulation Study
  – Complete screening simulations
  – Pick and optimize high-potential options
  – Optimize control with evolutionary algorithms

• AISs schematic designs that integrate simulation results

Building envelope systems with AIS can significantly
• reduce energy for heating and cooling (up to 70% from free energy sources in first iteration of screening study)
• provide grid services (shed, shift, and even modulate loads) in all climate zones to make the building envelope an efficient active component
Thank You

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REFERENCE SLIDES
Project Budget

Project Budget: $350K  
Cost to Date: ~$136K

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<th>FY 2018</th>
<th>FY 2019 (current)</th>
<th>FY 2020 – FY 2021 (planned)</th>
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TBD: To Be Determined
# Project Plan and Schedule

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<th>11/18</th>
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| Task 2: Feasibility Analysis            |       |       |       |       |       |       |       |       |       |       |       |       |
| General preparation                     |       |       |       |       |       |       |       |       |       |       |       |       |
| Simulation model set-up                 |       |       |       |       |       |       |       |       |       |       |       |       |
| Logic implementation for control       |       |       |       |       |       |       |       |       |       |       |       |       |
| Full-scale parametric study            |       |       |       |       |       |       |       |       |       |       |       |       |
| Set-up full-scale parametric simulations|       |       |       |       |       |       |       |       |       |       |       |       |
| Run and assess full-scale parametric simulations |       |       |       |       |       |       |       |       |       |       |       |       |
| Identify options with potential        |       |       |       |       |       |       |       |       |       |       |       |       |
| In-dept simulation study               |       |       |       |       |       |       |       |       |       |       |       |       |
| Iterative control improvement          |       |       |       |       |       |       |       |       |       |       |       |       |
| Summarize full-scale and in-depth parametric simulation study |       |       |       |       |       |       |       |       |       |       |       |       |
| Identify ideal scenarios               |       |       |       |       |       |       |       |       |       |       |       |       |

| Task 3: Initial Development of Active Insulation Systems |       |       |       |       |       |       |       |       |       |       |       |       |
| Combine information                      |       |       |       |       |       |       |       |       |       |       |       |       |
| Identify conductivity range, applications |       |       |       |       |       |       |       |       |       |       |       |       |
| Identify large scale manufacturing requirements |       |       |       |       |       |       |       |       |       |       |       |       |
| Identify cost effectiveness              |       |       |       |       |       |       |       |       |       |       |       |       |
| Schematic designs                       |       |       |       |       |       |       |       |       |       |       |       |       |
| Describe schematic designs              |       |       |       |       |       |       |       |       |       |       |       |       |

- **Task 1: Assessment of the State-of-the-Art**
  - Literature review
  - Technologies and systems
  - Simulation methods, tools, controls
  - Optimization control
  - Identification of research gaps
  - Establish simulation procedure
  - Simulation tool
  - Building models
  - System modeling
  - Application scenarios
  - Scoping study set-up
  - Report

- **Task 2: Feasibility Analysis**
  - General preparation
    - Simulation model set-up
    - Logic implementation for control
  - Full-scale parametric study
    - Set-up full-scale parametric simulations
    - Run and assess full-scale parametric simulations
    - Identify options with potential
  - In-dept simulation study
    - Iterative control improvement
    - Summarize full-scale and in-depth parametric simulation study
    - Identify ideal scenarios

- **Task 3: Initial Development of Active Insulation Systems**
  - Combine information
    - Identify conductivity range, applications
    - Identify large scale manufacturing requirements
    - Identify cost effectiveness
  - Schematic designs
    - Describe schematic designs
## Deliverables and Milestones

<table>
<thead>
<tr>
<th>Deliverables/Milestones</th>
<th>Due date</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submitted a summary of the literature to guide the research</td>
<td>12/31/18</td>
<td>Regular</td>
</tr>
<tr>
<td>Established a simulation procedure for a 6-month scoping study</td>
<td>12/31/18</td>
<td>Regular</td>
</tr>
<tr>
<td>Integrated logic, thermal, and optimization control models for selected residential and/or commercial prototype buildings into simulation environment</td>
<td>3/30/19</td>
<td>Regular</td>
</tr>
<tr>
<td>Identified example implementation scenarios for active insulation systems</td>
<td>6/30/19</td>
<td>Regular</td>
</tr>
<tr>
<td>Completed summary of simulation results on potential energy savings estimates and benefits to the grid. Decide on: Energy consumption and peak loads can be decreased by at least 20%</td>
<td>6/30/19</td>
<td>Go/No Go</td>
</tr>
<tr>
<td>Submitted schematic designs for two AISs based on info gathered in Tasks 1 and 2</td>
<td>9/30/19</td>
<td>Regular</td>
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