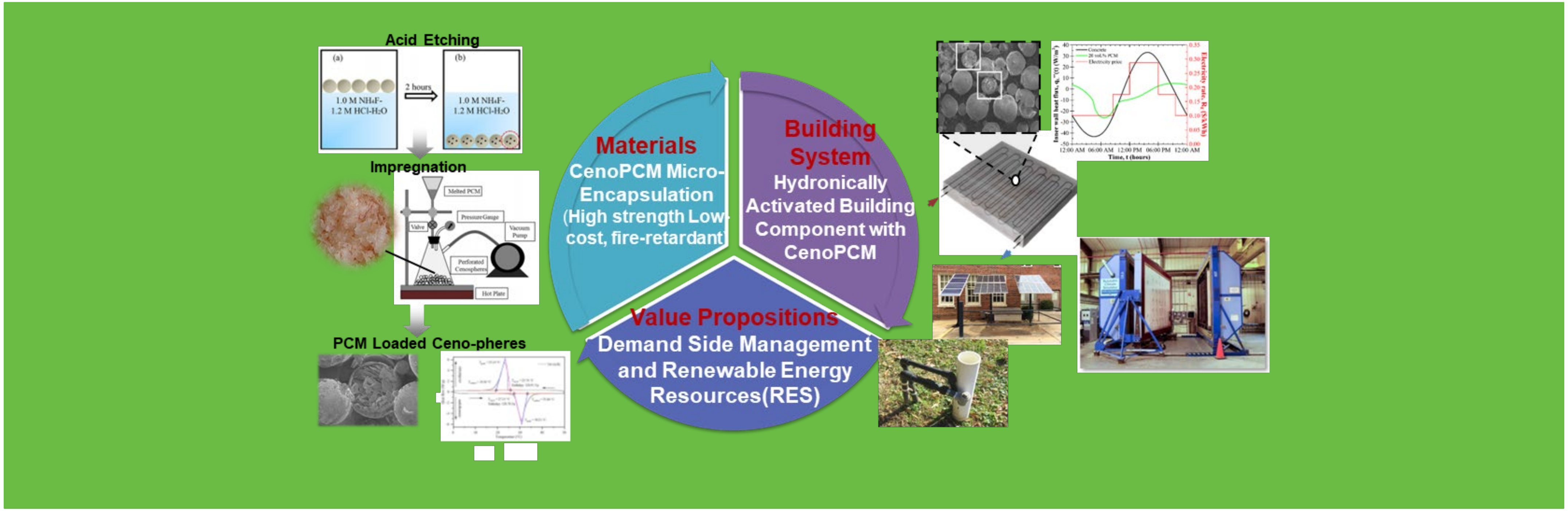
Cost-effective Thermally Activated Building Systems to Support a Power Grid System With High Penetrations of As-available Renewable Energy Resources



Performing Organization(s): The University of Alabama, Tuscaloosa
PI Name and Title: Jialai Wang, Ph.D., P.E., Professor
PI Tel and/or Email: (205)348-6786; jwang@eng.ua.edu

Project Summary

Timeline:

Start date: August 1, 2019

Planned end date: 12/31/2022

Key Milestones (insert 2-3 key milestones and dates)

1. Milestone 2.1.1; 07/31/2020
2. Milestone 2.2; 07/31/2020
3. Milestone 8.1.2, 1/31/2021

Budget:

Total Project $ to Date:

- DOE: $752,234.
- Cost Share: $160,294.

Total Project $:

- DOE: $1,499,969
- Cost Share: $375,020

Key Partners:

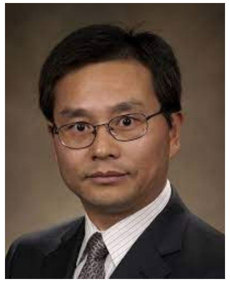
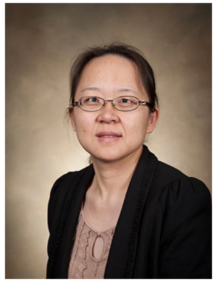
Texas A&M University
The University of Tennessee, Knoxiville
Oak Ridge National Laboratory
Sutterlin Technologies, LLC

Project Outcome:

1. A novel fire-retarded PCM microcapsules suitable for building applications in the U.S. with the cost of no more than $50/kWh.

2. At least 15% reduction on energy cost of operating buildings through integrating the new PCM-based thermal energy storage system with the hydronic activation and supporting better building-to-grid integration with high penetrations of as-available renewable energy source.

Team

PI Jialai Wang, Professor of Civil, Construction, and Environmental Engineering, The University of Alabama

- 20+ years of research experience in construction and building materials.
- Microencapsulation technology of PCM with Cenosphere, project coordination and reporting.

Co-PI Zheng O'Neill, Associate professor of Mechanical Engineering, Texas A&M University

- 20+ years of experience in integrated building energy and control systems design, modeling and optimization, and net-zero energy buildings.
- Evaluations the benefits of the proposed PCM-TES system through simulation.

Co-PI William Sutterlin, Founder and the president of Sutterlin Technologies, LLC

- 15+ years of experience PCM industry, holding 50 U.S. Patents and Applications.
- Development of low-cost PCM using underutilized bio-based products, and commercialization and industrial outreach.

Co-PI Hongyu Zhou, Assistant professor of Civil and Environmental Engineering, The University of Tennessee, Knoxville

- Structural and material engineering and energy efficient building systems.

Material modeling and prototype development and testing.

Co-PI Som Shrestha, Building Scientist at ORNL

- Experimental and analytical studies to improve the energy performance of building envelope components, equipment, and systems.
- Materials characterization and large-scale evaluations of thermal performance of building components with PCMs

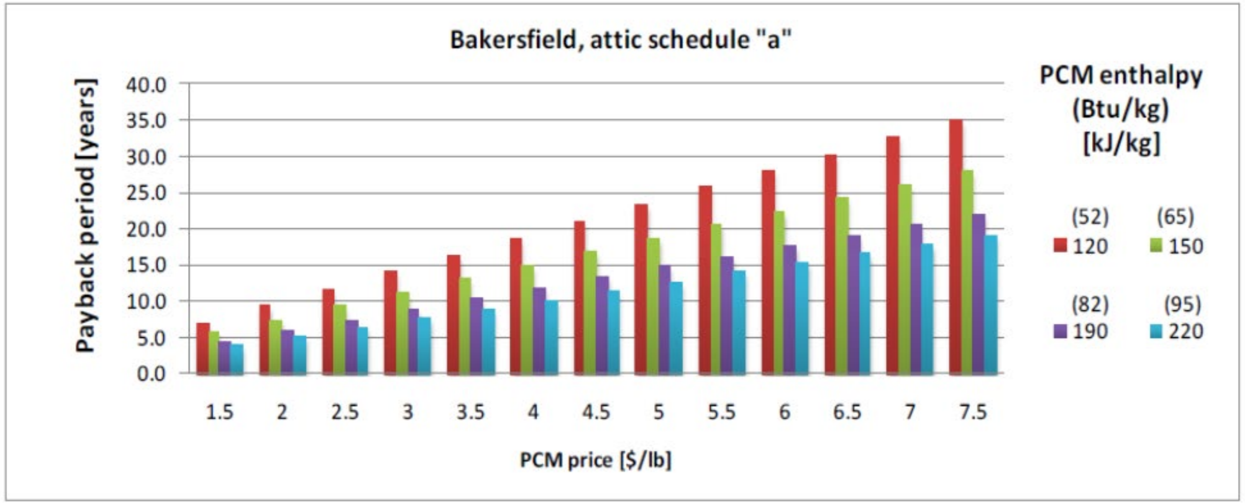
Co-PI Xiaobing Liu, R&D Staff in the Building Equipment Research Group at ORNL

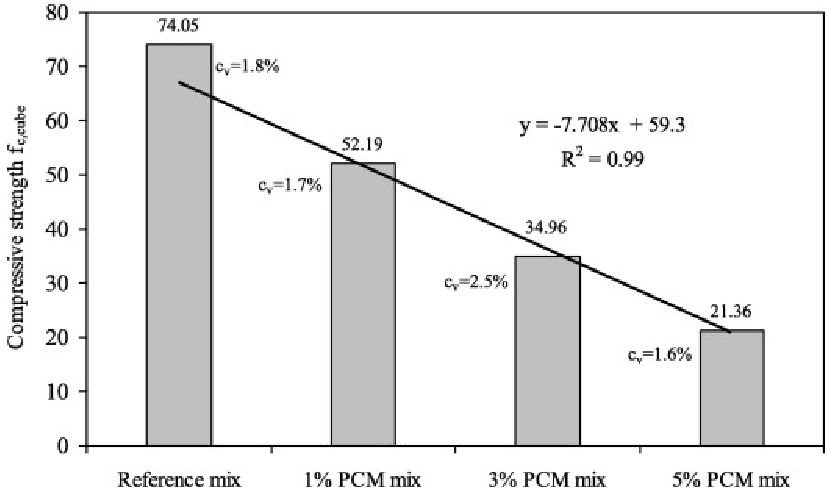
- Principal Investigator of many HVAC related R&D projects
- Modeling and experimental evaluation of thermal energy storage system using phase change materials

Challenge

US building occupants spend over $410 billion per year on energy bill. About 39% of total primary building energy consumption can be attributed to losses through building envelope. Therefore, this enormous energy cost can be effectively reduced by integrating PCM into building envelop to provide storage of thermal energy in buildings to flatten heating and cooling load profiles and to minimize peak energy demands. Up to 22% energy saving can be achieved according to a recent study. However, current available PCM and its microcapsules face a few keys challenges

- Too expensive, payback period over 10 years.
- Not compactible with building materials: flammable, mechanically vulnerable.
- Thermal storage capacity only available in hot days.
- Benefits of using PCM not quantified.





Approach-I

Material innovations: Develop a low-cost PCM microcapsule (CenoPCM)

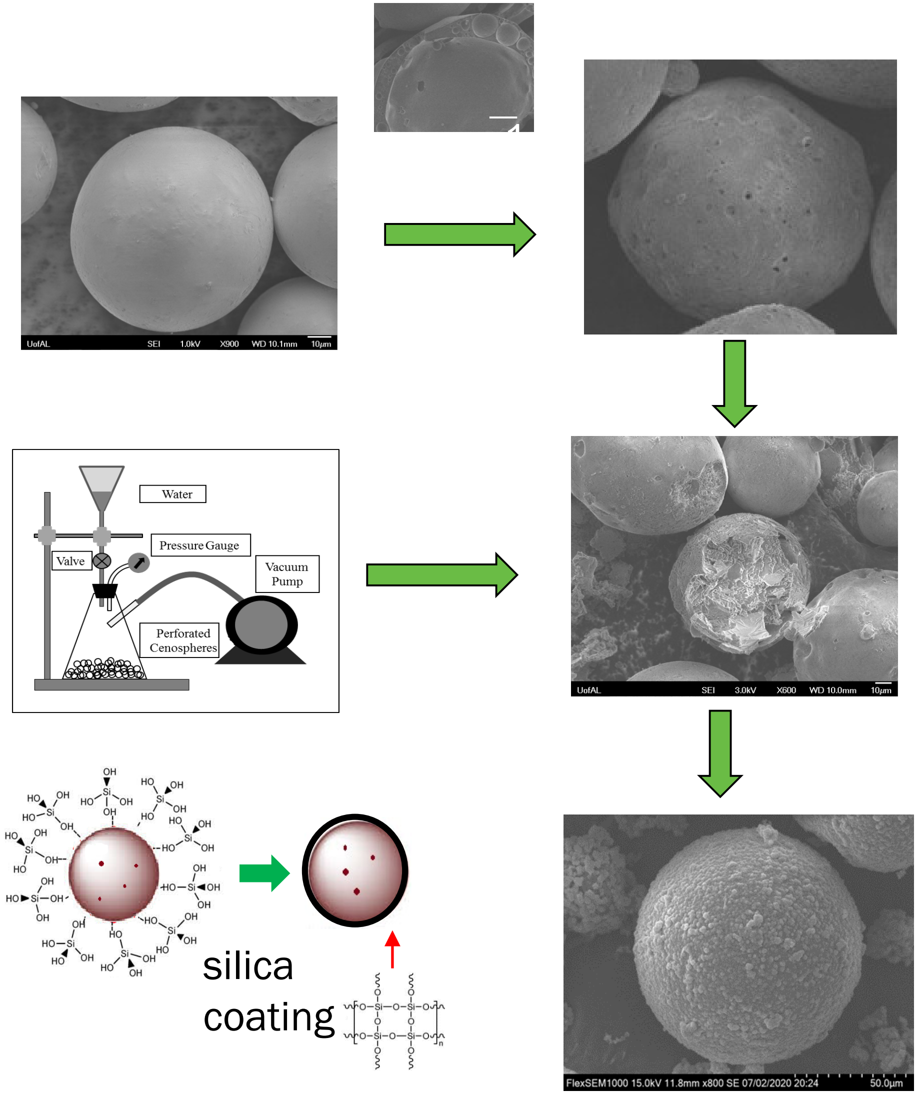
- A novel microencapsulation technology using cenospheres
  - Low cost
  - Non-combustible
  - Mechanical strong and durable
  - Higher thermal conductivity

- Low-cost PCM based on underutilized bio-based product, soapstock
  - The lowest cost vegetable oil material comes from a waste stream produced from the refining process

1. Chemical etching

2. Impregnating

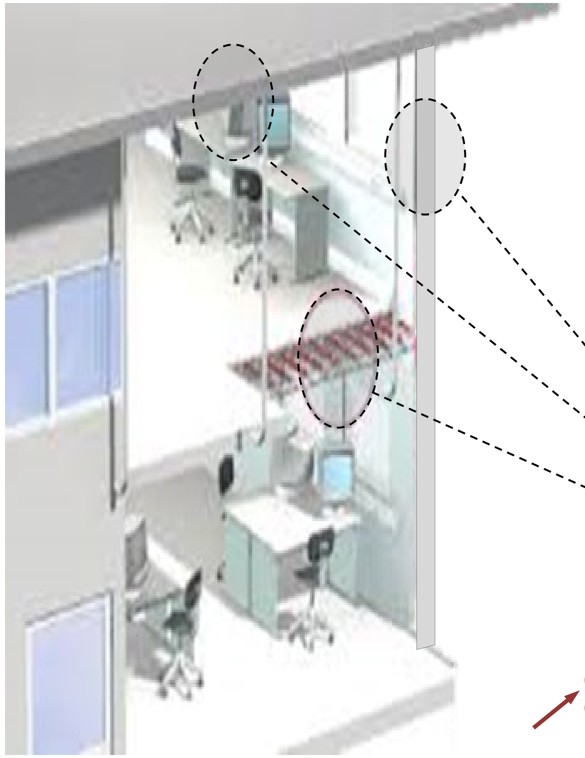
3. Sealing the holes



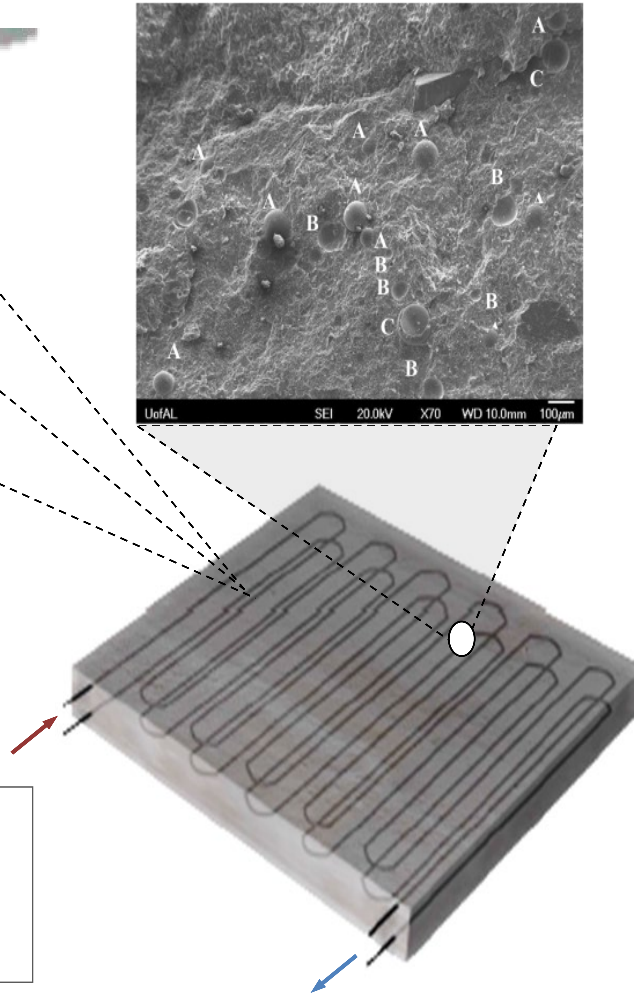
Approach-II

Subsystem Innovation (Integration of CenoPCM with hydronic heating/cooling): an innovative thermal active panel

- Integrated with CenoPCM
- Embedded with capillary tubes, which functions as thermal energy storage unit using heat sink and source from solar-thermal collector and ground loop heat exchanger.
  - Latent heat of PCM is mobilized whenever needed by the hydronic activation
- High mechanical strength with function as structural member.
  - Simplifying building system
  - Saving materials and space



- Floor slab
- Ceiling
- Exterior wall



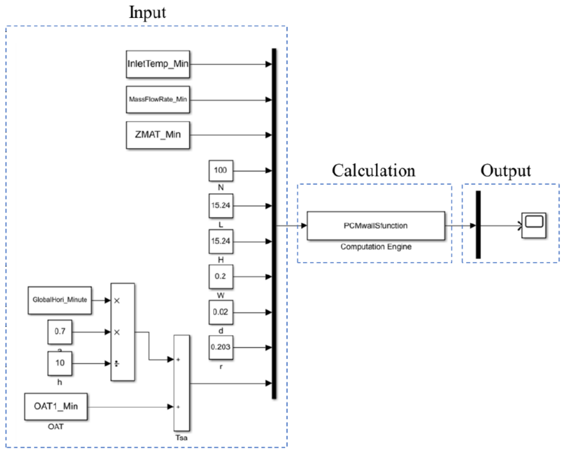
Proposed thermally activated building envelope unit

Approach-III

- System-level Innovation: a novel integration of the envelope panel with PCM and capillary network
  - support renewable energy sources (RES) for the power grid reliability, quality, resilience, and dispatchability
  - Optimize design and operation together with HVAC and control

- Develop simulation tool to verify and optimize the proposed technique and quantify the benefit of PCM in building envelope.

- Confirm the of thermal and structural performance of the proposed thermally activated structures through full-scale laboratory evaluation



Impact

- Advance practical application of microencapsulated PCM in building materials for energy saving. Due to use of industrial waste, hollow fly ash as the shell for the microcapsule, the CenoPCM have many competitive advantages for building applications over existing products:
  - lower cost (<$50/kWh, which is drastically lower than any existing organic PCM based microcapsule)
  - non-flammable, higher mechanical strength, higher thermal conductivity, better compatibility with traditional building materials.

- Shape the building design for energy saving by using multifunctional structural panel which uses less space and has potential to reduce or eliminate the need for ductwork and heat transfer terminals inside a building and reduce the HVAC equipment size.

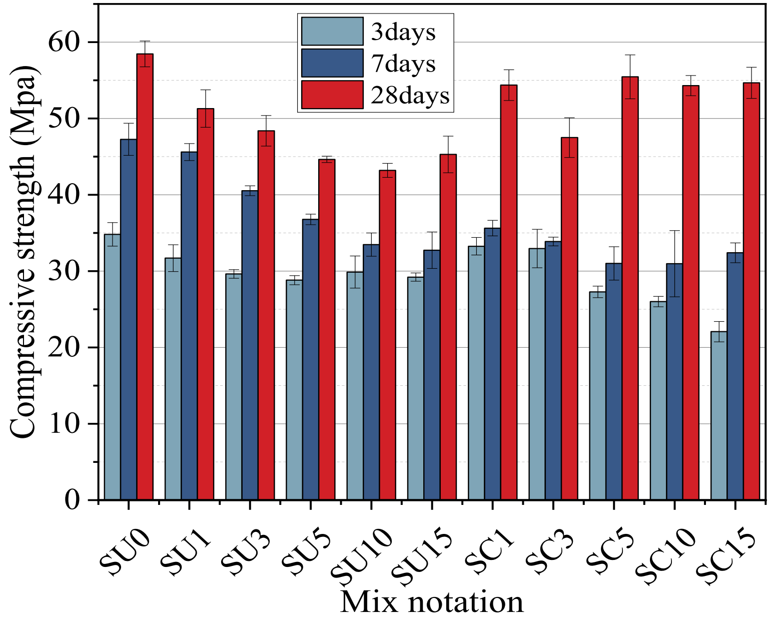
- Enable high efficiency use of renewable energy use of renewable energy sources and improve resilience and reliability of the power grid by providing ancillary services of operation reserve to the power grid through effective demand reduction and load leveling.

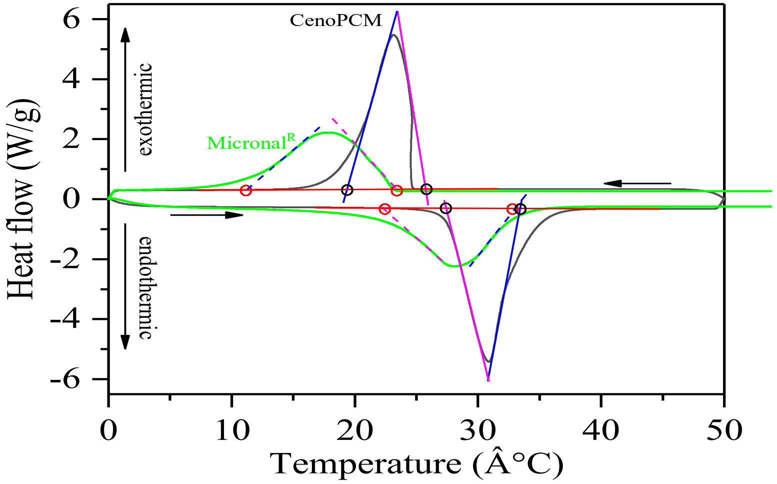
- The proposed thermally activated building envelope units can achieve more than 15% energy saving confirmed by testing. Primary energy savings anticipated to be achieved across the U.S. building stock is equal to approximately 0.77 Quads (770 TBtus).

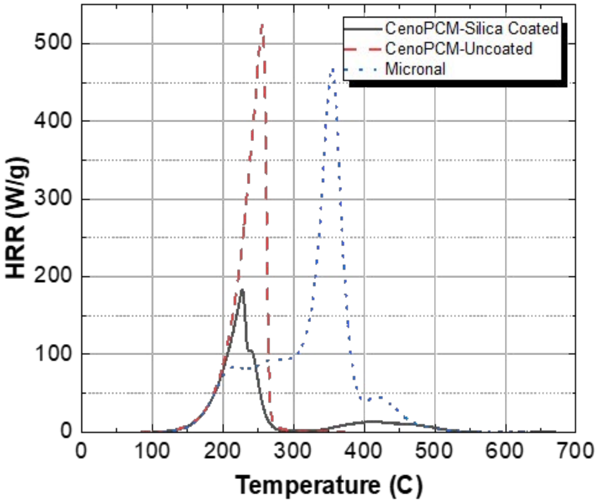
Progress I

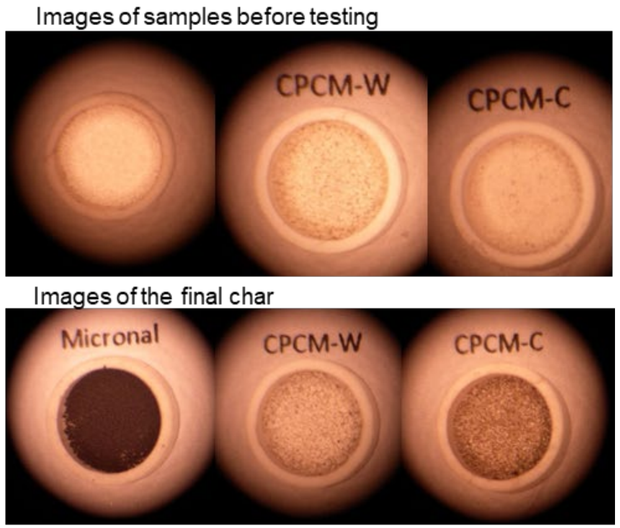
CenoPCM microcapsule has been successfully developed

- Crushing strength > 5 Mpa
- Latent heat > 125 J/g
- Supercooling < 2 ℃
- glide temperature < 7℃
- Cost < $50/kWh
- No reduction on concrete strength due to silica coating
- CenoPCM outperforming Micronal by at least 50%





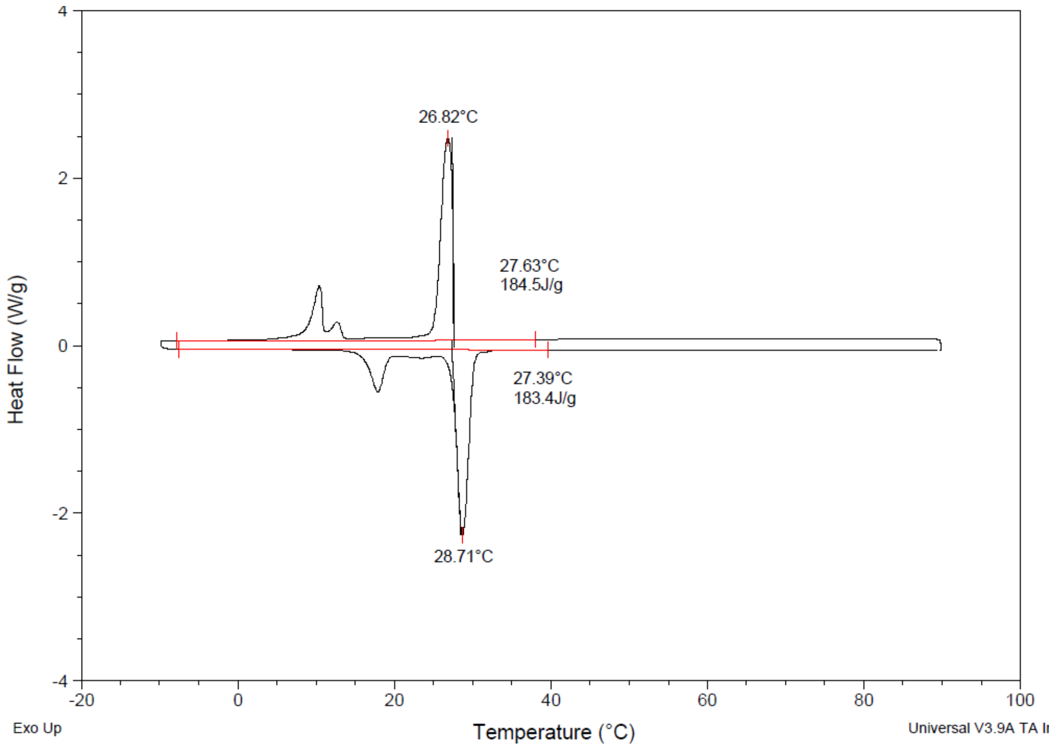




Progress II

Soapstock based PCM has been successfully manufactured

- The two main types of organic PCMs are fatty acid and paraffin based.
  - Paraffin based PCMs are petroleum sourced and have prices higher than $3.00/lb.
  - Fatty acids are sourced from vegetable oil sources such as soybean oil, corn oil, coconut oil and palm oil.
  - The price of vegetable oils has risen to ~$0.60-0.65/lb. Conversion cost for a vegetable oil to fatty acid PCMs is ~$0.25-0.35/lb. Therefore, a fatty acid based PCM has a cost of no less than $1.00/lb.
- The lowest cost vegetable oil material comes from a waste stream produced from the refining process called "Soapstock." Soapstock has a price of ~$0.05/lb.
- Initial estimates are that we can convert this waste stream to fatty acid PCMs at $0.30-0.40/lb with a total PCM cost of $0.35-0.45/lb

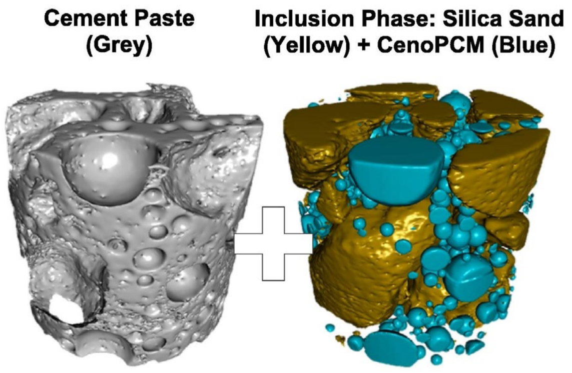


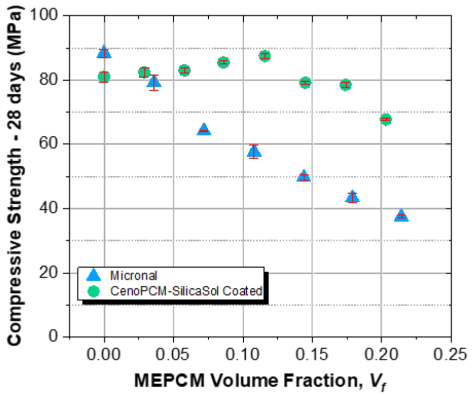
DSC of a Soapstock Based PCM. The smaller peaks on the left are from some impurities. However, it is not necessary to remove these for a good low cost PCM.

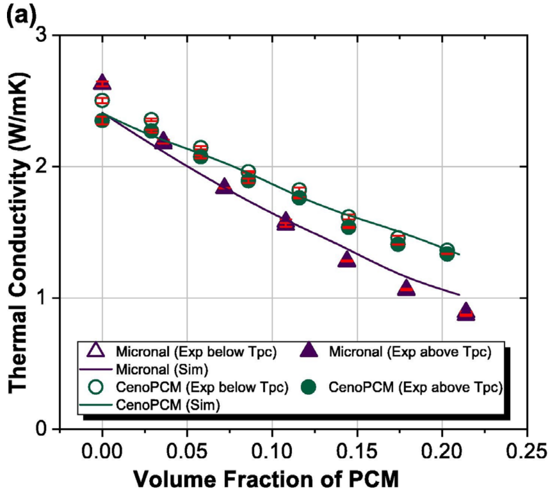
Progress III

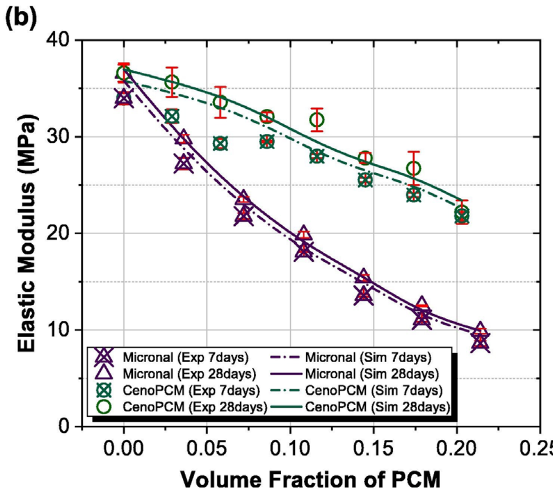
Cementitious Composite with CenoPCM have been successfully developed.

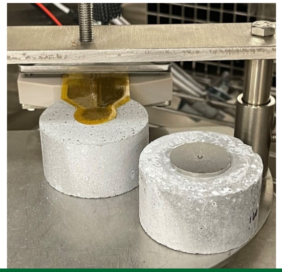
– Optimal mix design is completed
– Model predicting the thermo-mechanical performance of materials with CenoPCM is completed.
– CenoPCM inducing a strength gain until a critical volume is reached.
– CenoPCM showed a maximum strength los of less than 20% at the maximum volume loading
– Rigid shelled CenoPCM allows for the Elastic Modulus reduction to be decrease by 40% less than the soft shelled Micronal
– Maintained less that 50% reduction for all but the highest concentration of MEPCM
– Higher thermal conductivity is achieved in sample with CenoPCM





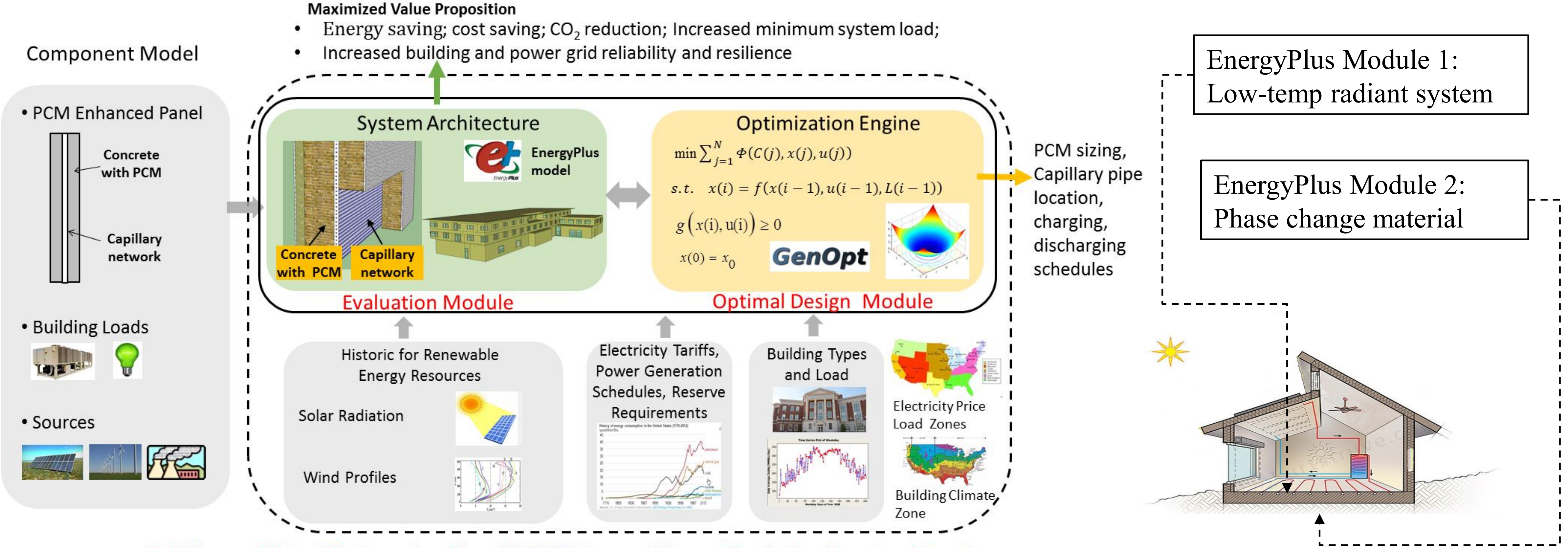






Progress IV

The EnergyPlus based evaluation framework developed and tested using DOE prototype medium-sized office building model



Buildings as Virtual Battery via a Novel PCM Enhanced Thermally- Active Structural Panel

- EnergyPlus PCM two-curve model was updated with a two-phase static hysteresis model by modifying source codes.
- Optimization has been conducted on the high-performance computing cluster.
- Preliminary daily results show about 50 % operation cost saving compared with DOE prototype building in a mild day.

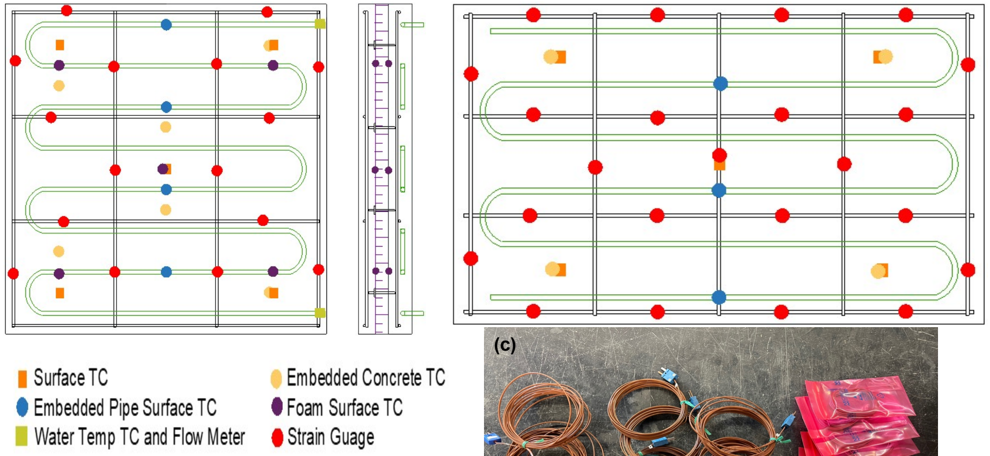
Progress V

Full scale laboratory verification

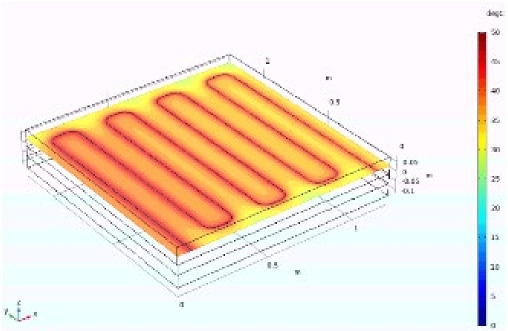
- Numerical simulation guided the design of the thermally activated PCM panel for lab test is completed
- Completed instrumentation plan and acquired sensors for laboratory evaluations.

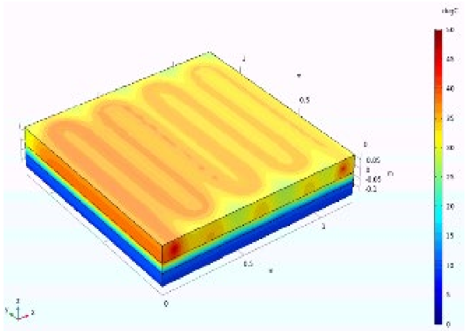
Instrumentation summary for exterior precast wall panel (thermocouples (TCs))

Locations	Embedded/On Surface	One surface	Total (two surfaced)
Surface TCs	Surface	5	10
Embedded Concrete TCs	Embedded	6	
Foam Surface TCs	Embedded	5	10
Embedded Pipe Surface TCs	Embedded	4	



Instrumentation plan





Preliminary analysis of the exterior precast wall panel in COMSOL

Mold construction

Stakeholder Engagement

The research team has successfully completed NSF I-Corps customer discovery program

- Conducted 107 customer interviews
- Meeting with various stakeholders
    - PCM manufacturers and suppliers
    - Building materials manufactures and trade organizations
    - End users
    - Influencers
    - Investors and incubators
- Identified partners for future commercialization

Remaining Project Work

UA

Task 11.0: Reducing the cost of bio-based PCM (M13-24)

- Subtask 11.1: Reducing the cost of bio-based PCM
- Subtask 11.2: Optimizing loading/sealing process of PCM

Task 12.0: Technology to Market (M24)

- Subtask 12.1: Market study, commercialization strategy, and manufacturing scalability analysis
- Subtask 12.2: Cost model update

Task 15.0: Reducing the cost of CenoPCM through material optimization (M25-36)

Task 16.0: Technology to Market (M36)

- Subtask 16.1: Cost model update
- Subtask 16.2: Next-stage funding and transition plan for further development and commercialization

Remaining Project Work

ORNL

- **Subtask 10.1: Set up experimental apparatus and data acquisition system to evaluate thermally activated building components (M19-24)**
  - A holding structure will be developed to fit the prototype component developed in Task 8.0 into a rotatable guarded hotbox (RGHB)
  - Constant temperature bath will be used to control the circulating water temperature

RGHB

- **Subtask 13.1 Evaluate selected thermally activated building components at controlled conditions (M25-30)**
  - Steady-state and transient tests to capture the impact of thermal mass
  - Calibrate the COMSOL models with the lab test results

Remaining Project Work

UTK

- Subtask 8.2: Component Prototyping (M19-24)
  - Floor slabs: one reinforced concrete benchmark, two with CenoPCM of different volume concentrations and hydronic loops
  - Exterior precast wall panels: one reinforced concrete benchmark, two with CenoPCM of different volume concentrations and hydronic loops

- Subtask 13.2: Full-scale laboratory evaluation of structural behavior (M25-33)
  - Four-point bending test of the flexural behavior of CenoPCM structural panel elements
  - Concentrated loading test of the punching shear behavior of floor slabs

Texas A&M

- Task 9.0: PCM-TES value propositions associated with demand side management and managing renewable energy resources (M13-24)

- Subtask 14.0: PCM-TES value propositions model validation (M25-33)

Thank You

The University of Alabama
Jialai Wang, Ph.D., P.E., Professor
205-348-6786; jwang@eng.ua.edu

REFERENCE SLIDES

Project Budget

Project Budget: Outline the project budget and history.
Variances: Describe any variances from original planned budget and identify if/how the project plan was modified.
Cost to Date: Identify what portion of the project budget has been expended to date.
Additional Funding: Note, if any, other funding sources.

Budget History					
8/1/2019– FY 2020 (past)		FY 2021 (current)		FY 2022 – Insert End Date (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$481,878	$120,418	$585,340	$148,694	$432,751	$105,953

Project Plan and Schedule