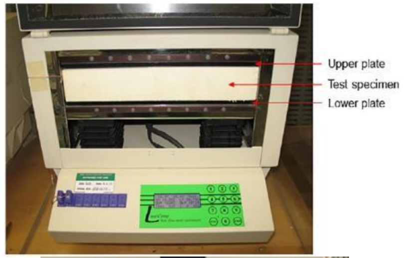
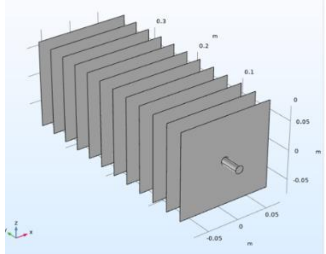
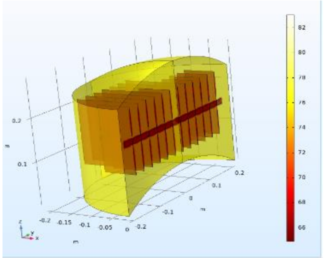
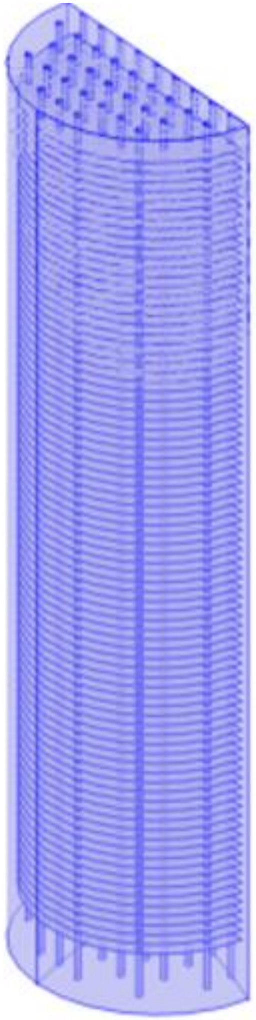
Development of TES systems for thermally anisotropic building envelopes (TABE)









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BTO-03.01.03.12, AOP

Project Summary

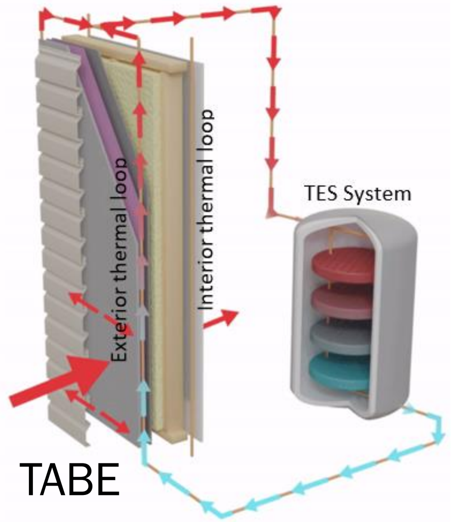
Objectives:

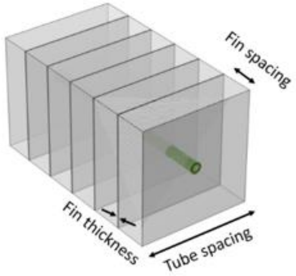
Design, build and evaluate a TES system

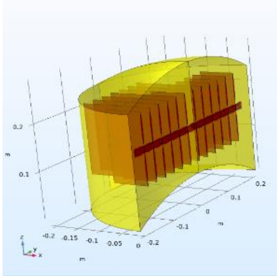
- High-performance
    - Charge/Discharge 75% in 3 hours with ΔT < 10 °F
    - Charge/Discharge 90% in 4 hours with ΔT < 10 °F
    - Utilize 90% of the storage volume with PCM
- Low-cost (<$30/kWh)
- Suitable to integrate with TABE

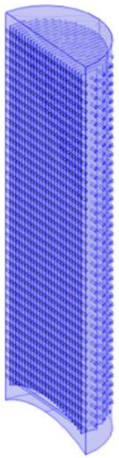
Outcome:

Integrate TES with TABE to realize 50% energy cost savings and load-shifting.









Team

Oak Ridge National Laboratory

Stats

Performance Period: 10/01/2021 to 09/30/24

DOE budget: $975K

- Milestone 1: Design TES systems that meet the high-performance goals.
- Milestone 2: Volumetric energy density of the TES system maintained over 95% after 100 cycles.
- Milestone 3: Field demonstration 50% energy cost savings and peak demand reduction when the TES is connected to the TABE.

Problem

- TES connected with TABE can save energy and reduce peak demand. However, TES suitable to integrate with TABE is not available.
- Most commercially available TES systems are large ice tanks
  - Suitable to integrate with central chillers
  - Not suitable to integrate with TABE (too low melting temperature, 32°F)
- New TES designs are required
  - Phase change temperature close to indoor temperature (68 to 79°F)
  - Maximize the use of TES systems and the potential energy savings

Solution

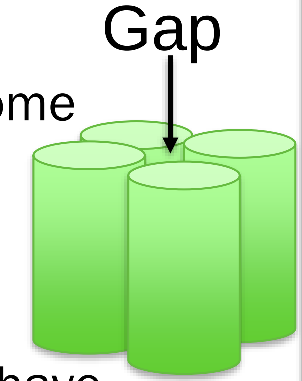
Low-cost fin and tube heat exchangers for use with low conductivity PCMs

- Bulk materials testing
- 3D FEM modeling with the complex physics captured empirically
- Design optimization
- Scaled experimental work with field deployment for control development

Subproblem- Modeling PCM and State-of-the-art HX

Modeling

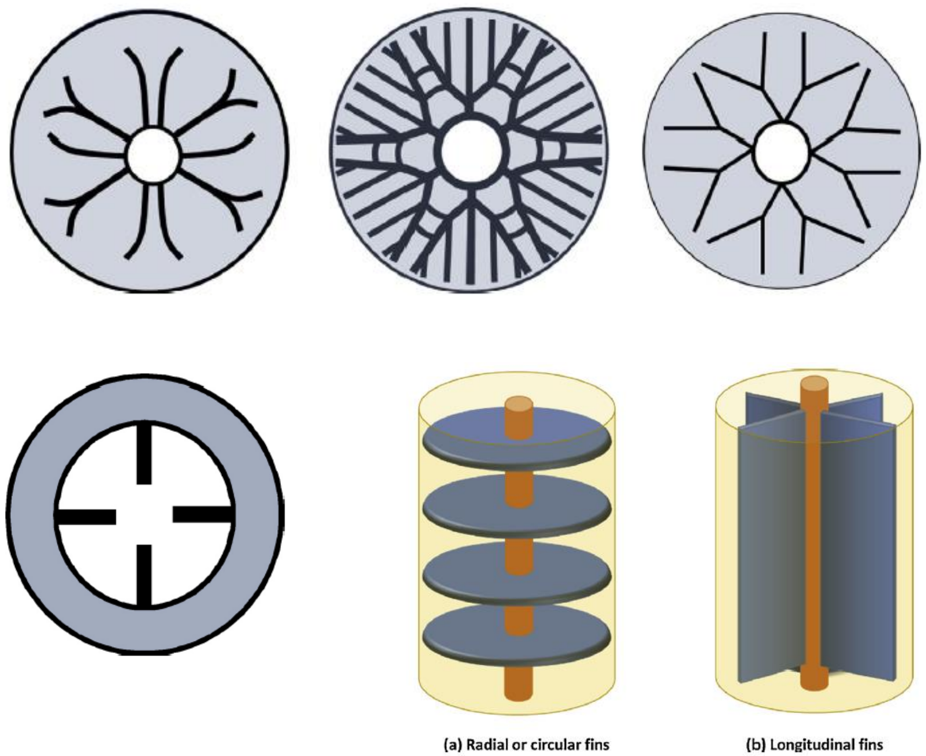
- Without proper physics-based modeling and selecting appropriate geometry the performance will not scale accurately.
- Not all energy storage properties are conserved over 1,000's of cycles for some PCMs.



Costs

- State-of-the-art heat exchangers often have complex geometry and are of high cost.
- >$100/kg 3D printed HX*
- SOA TES system is $600/kWh**

State-of-the-art fin and tube HX designs



L. Kalapala, J.K. Devanuri, J. Energy Storage. 20 (2018) 497–519. https://doi.org/10.1016/j.est.2018.10.024.

Designs in literature expensive or do not scale conservatively

*https://tcpoly.com/purchase-ice9-materials/
**https://www.thinkelectricheating.co.uk/product/sunamp-thermino-e/

Alignment and Impact

Successful TABE and TES integration

- Reduces energy consumption by 50%
- Allows shifting of load up to 4 hours of the 50% of the peak

Successful TES design is approaching DOE TES program goals for performance, cyclability, and costs

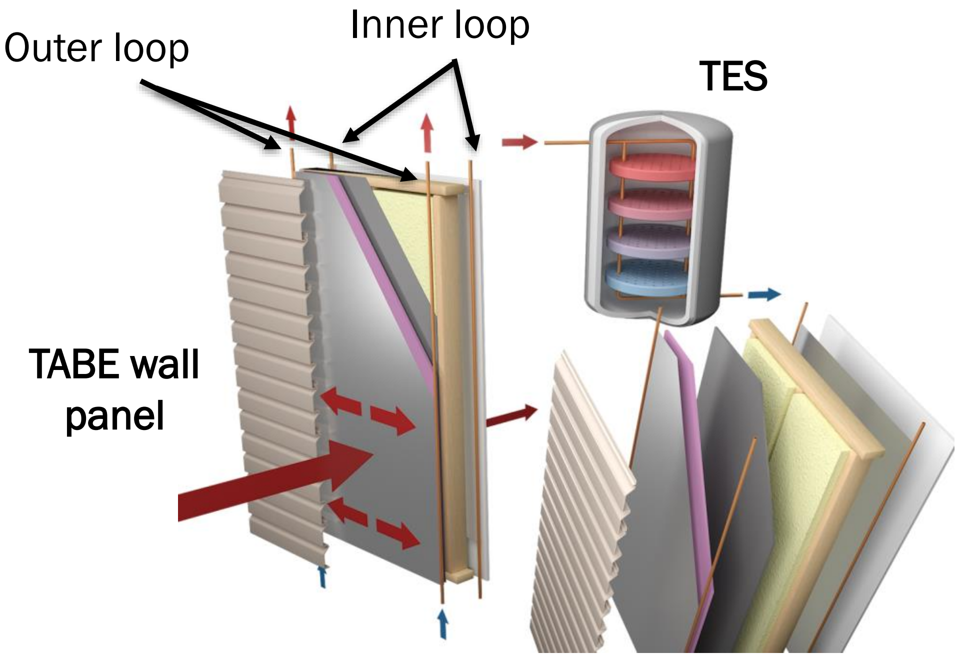
- Costs of heat exchanger < $5/kWh
- >90% of the storage volume is utilized as PCM
- Energy density > 50 kWh/m^3 at 10,000 cycles
- High heat transfer performance < 4 hours to charge or discharge 90% of storage

The objective of the TES subprogram is to enable shifting of 50% of thermal loads over four hours with a three-year installed cost payback. The system targets for the TES subprogram:

- <$15/kWh thermal
- >80 kWh/m3 energy density
- >10,000 cycles
- >200% charge/discharge rate over SOA

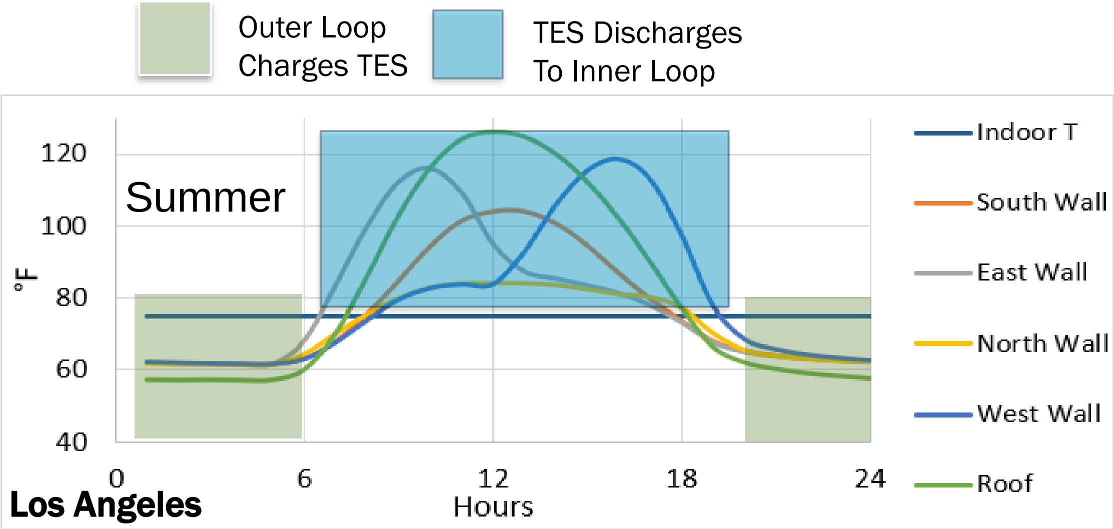
https://www.energy.gov/eere/buildings/thermal-energy-storage

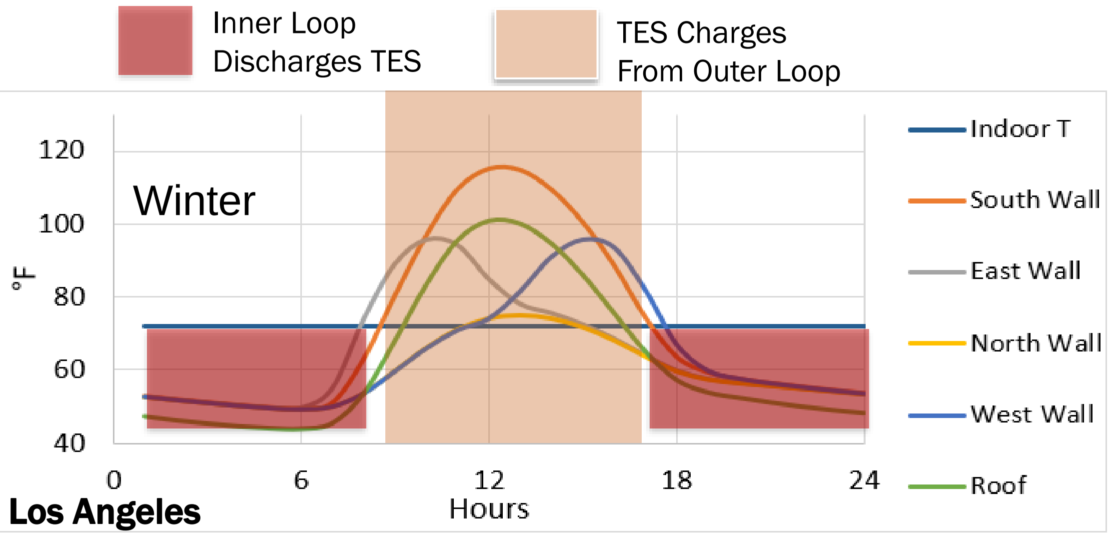
Approach: TABE System with TES



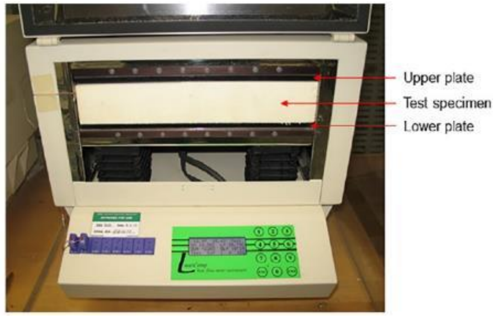
Project Goals (TES integration into TABE)

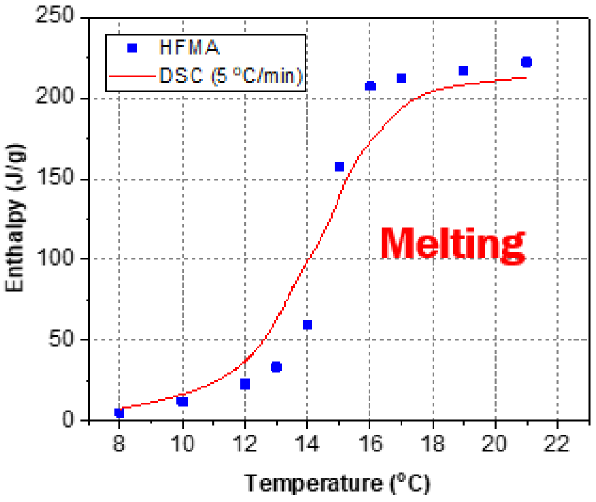
- ✓ Model, design and fabricate two PCM-based TES systems
- Optimize the TES design through laboratory experiments,
- Integrate the optimized TABE-TES system at a NET facility
- Performance of the full-scale integrated system.

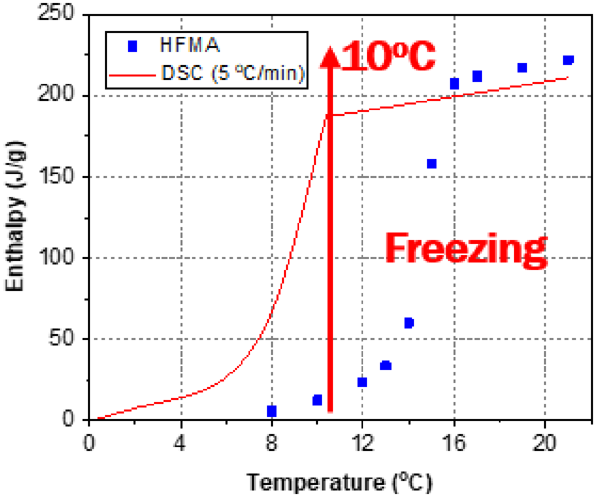




Approach: PCM Material Characterization







Differential Scan Calorimetry (DSC)

Heat Flow Meter Apparatus (HFMA)

DSC (ASTM D3418)

- Sample ~10 mg

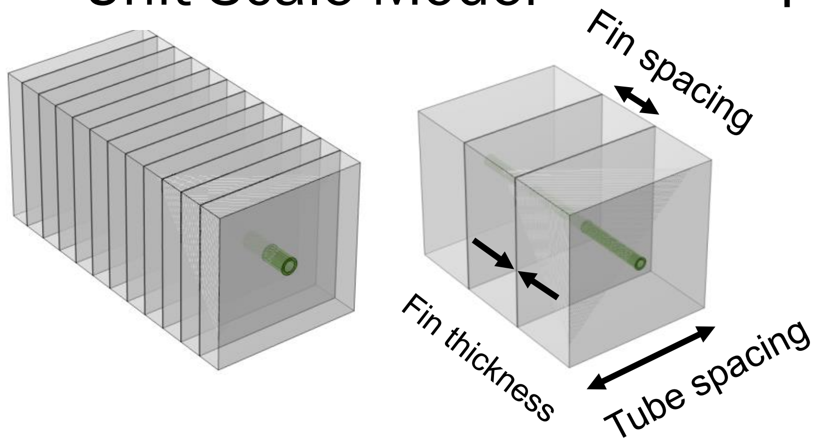
HFMA (ASTM C1784-20)

- Can capture bulk size properties (500 g)
- **More realistic heat rates**

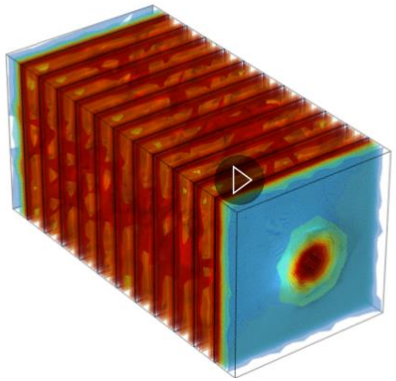
Bulk material testing allows for accurate models and closer to real-world performance

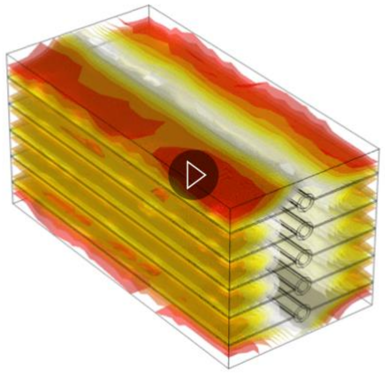
Approach: 3D Finite Element Modeling (FEM) Fin and Tube HX Design

Unit Scale Model

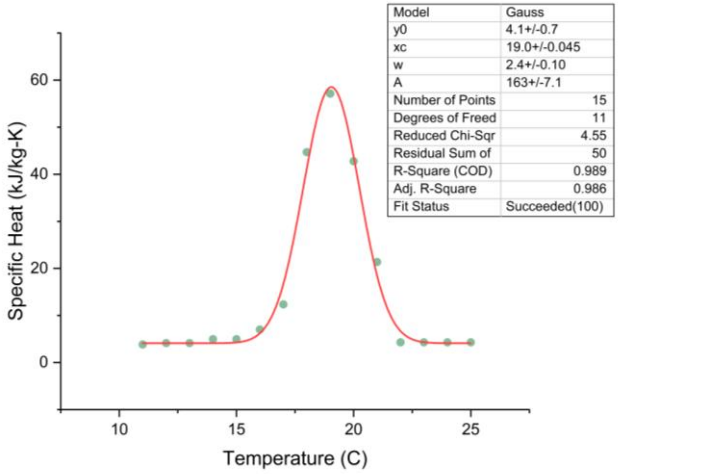


Perpendicular vs. Longitudinal fins





HFMA Measured Enthalpy



Parameters optimized by unit scale model

- Fin and tube configuration
- Volume and mass of heat exchanger
- Charge/Discharge performance
- Number of tubes

PCM model

$$C_p = \frac{1}{\rho}\left(\theta_1 \rho_1 C_{p,1} + \theta_2 \rho_2 C_{p,2}\right) + L_{1\to 2}\frac{\partial \alpha_m}{\partial T}$$

$$k = \theta_1 k_1 + \theta_2 k_2$$

$$\rho = \theta_1 \rho_1 + \theta_2 \rho_2$$

$$\alpha_m = \frac{1}{2}\frac{\theta_2 \rho_2 - \theta_1 \rho_1}{\theta_1 \rho_1 + \theta_2 \rho_2}$$

$$\theta = \theta_1 + \theta_2$$

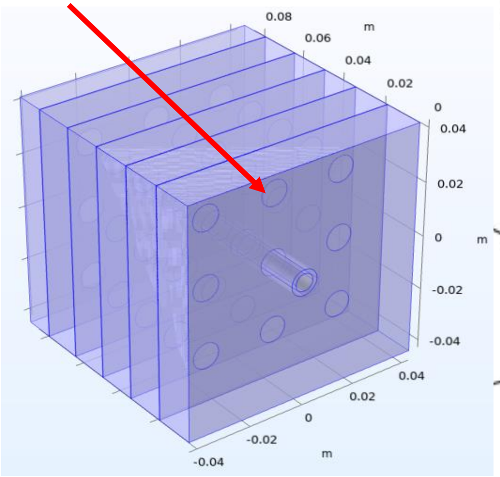
Physics captured

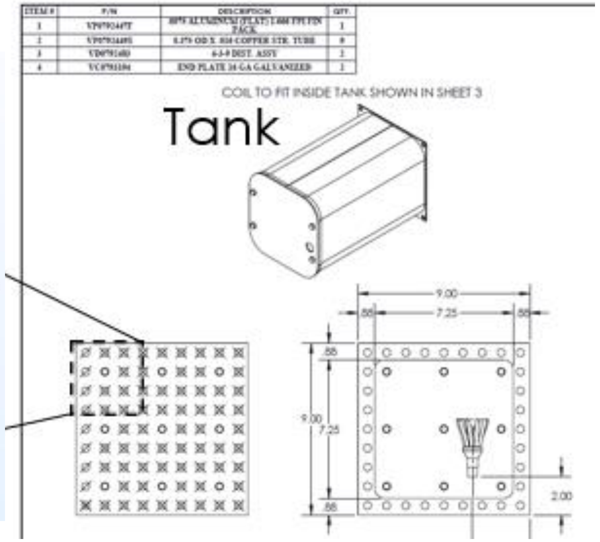
- Bulk PCM phase change behavior
- Range of melting temperature
- Melt/freeze front 3D
- Pulsed heat input
- Contact pressure

Design optimized while addressing the critical physics

Progress: 5-gallon 3D Finite Element Modeling (FEM) Fin and Tube HX Design

Perforated holes





Cost estimates for 5-gallon PCM heat exchanger

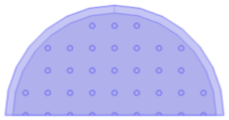
	Aluminum		Copper		Steel		Plastic/Steel	
Tubes (number)	9	9	9	9	9	9	9	9
Fin Thickness (inch)	1/128	1/16	1/128	1/16	1/128	1/16	1/128	1/16
Mass (lb)								
Fins	1.15	4.14	4.92	17.66	4.31	15.47	4.31	15.47
Tubes	0.13	0.13	0.54	0.54	0.48	0.48	0.06	0.06
Total	1.28	4.27	5.46	18.20	4.78	15.95	4.36	15.53
Cost ($)								
$/5 gallon with PCM (1.5x for OEM)	2.05	6.85	30.30	101.04	3.01	10.05	2.75	9.78
$/kJ to OEM	7.7E-4	2.6E-3	1.1E-2	3.9E-2	1.1E-3	3.9E-3	1.0E-3	3.8E-3
$/kWh to OEM	2.75	9.51	40.62	140.30	4.04	13.95	3.69	13.59
$/kWh to consumer w/o PCM	4.13	14.26	60.93	210.35	6.06	20.93	5.53	20.38

Novelty: Design scales conservatively, increases performance via natural convection paths

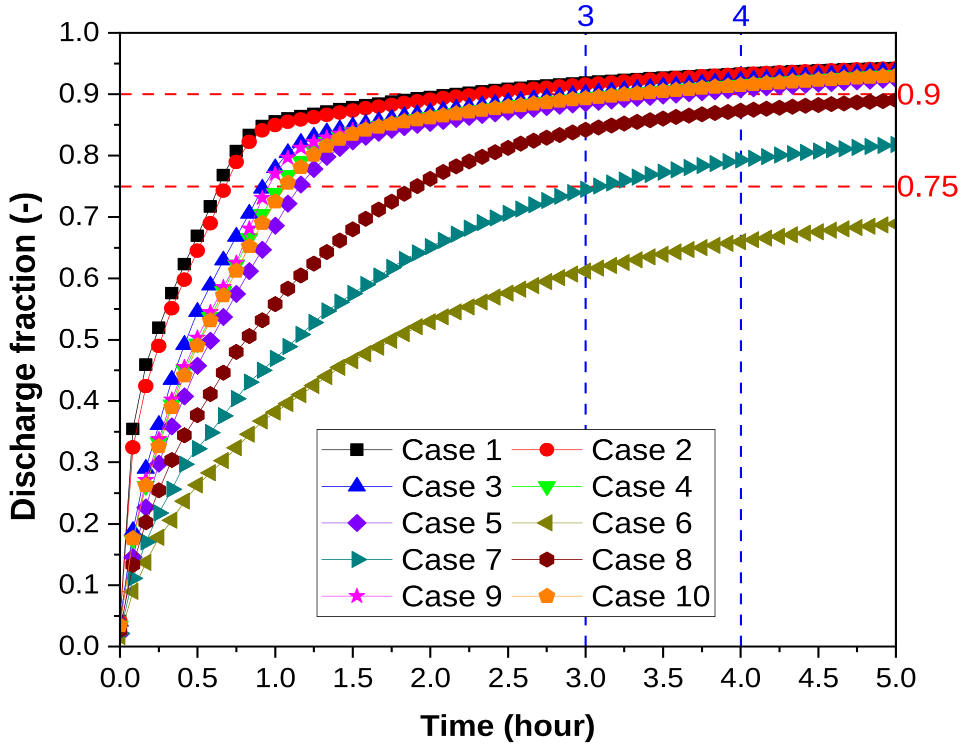
Novelty: HX costs very low per kWh
Market adoption of design expected
Design being built by manufacturer

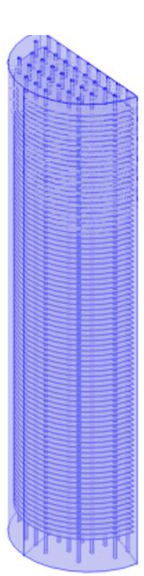
Progress: 50-gallon PCM HX Performance (3D FEM)

- Copper, Aluminum, PEX and Steel HX materials
- ΔT between HX and PCM phase change temperature
- Volume utilization of PCM > 90% (HX consumes < 10% of volumetric space)
- Discharge, >75% at 3 hours, >90% at 4 hours



Cases	Material (tube/fin)	ΔT (°F)	Discharge fraction in 4 hours (-)	Parameter sensitivity
1	Copper/Copper	10	0.93	Heat exchanger material
2	Aluminum/Aluminum	10	0.93	
3	PEX/Steel	10	0.90	
4	Copper/Copper	10	0.92	Mesh size
5	Copper/Copper	10	0.91	
6	Copper/Copper	3.7	0.66	Temperature difference btw HX and PCM
7	Copper/Copper	4.5	0.79	
8	Copper/Copper	6.3	0.87	
9	Copper/Copper	10	0.92	Phase change temperature range reduced to 8
10	Copper/Copper	10	0.91	Phase change temperature range increased to 10

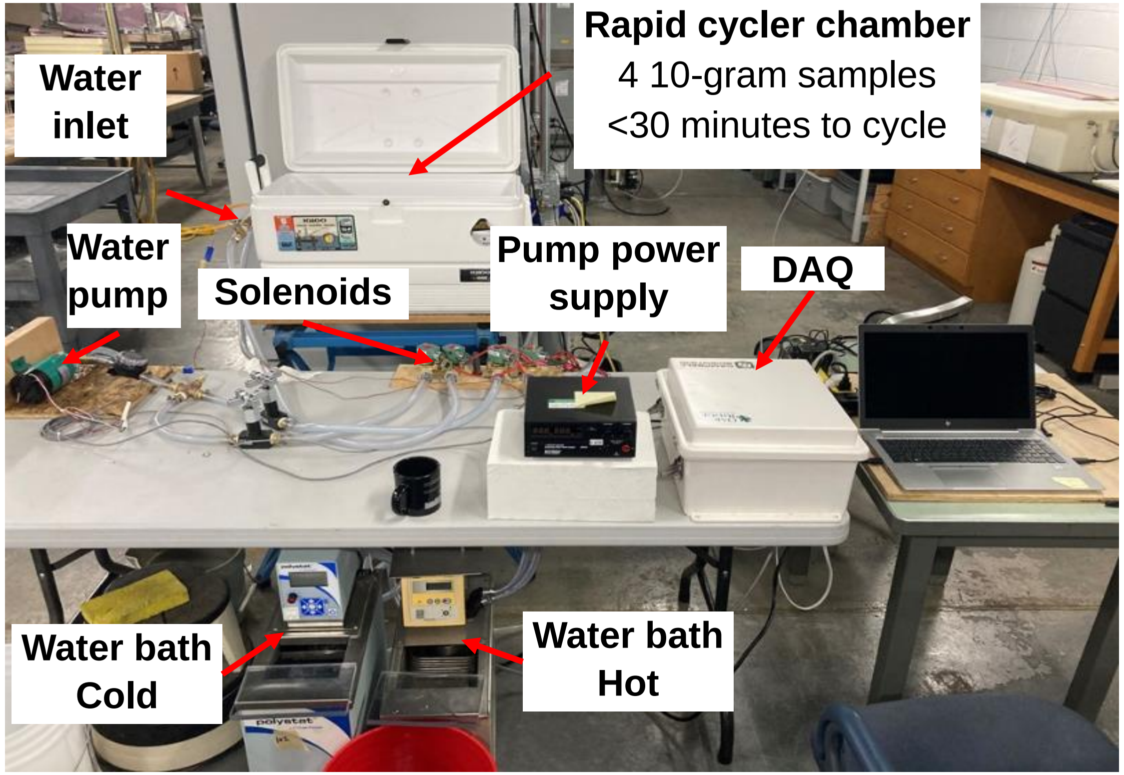




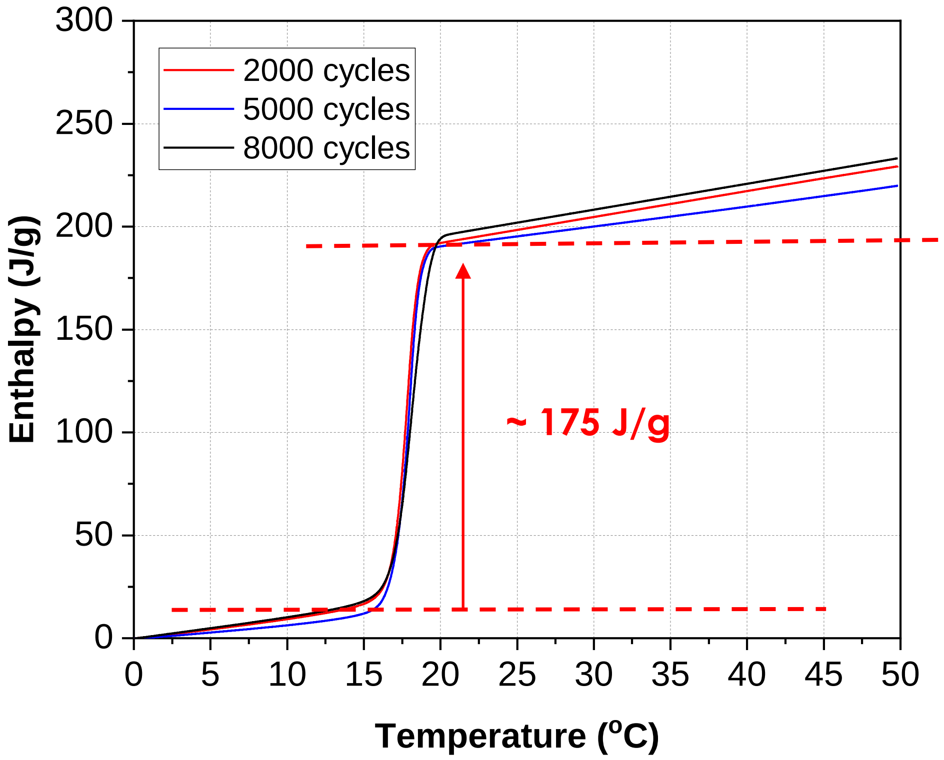
Milestone Met: Design TES systems that meet the high-performance goals

Progress: PCM Material Long Term Performance

Rapid Cycler



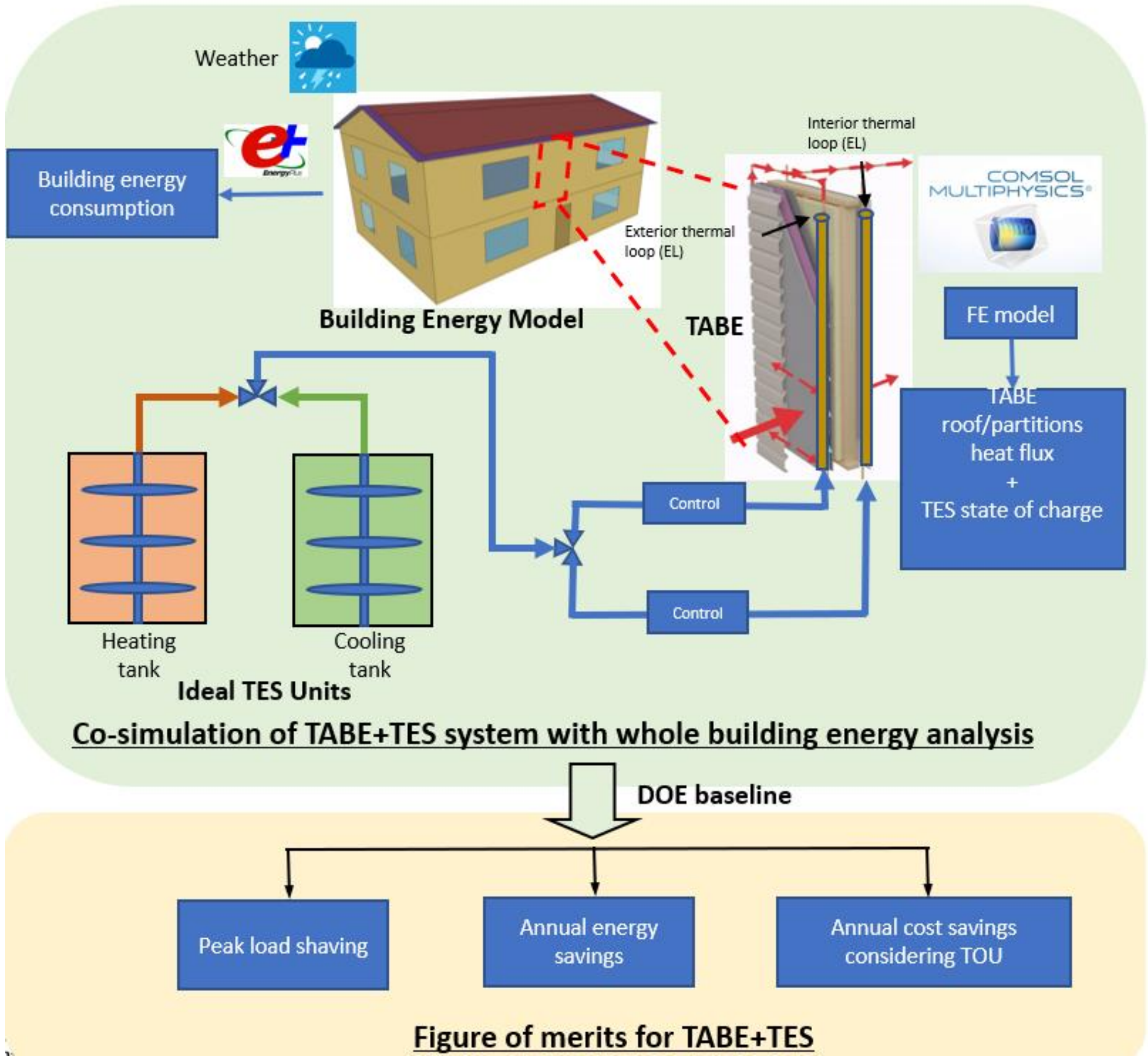
DSC



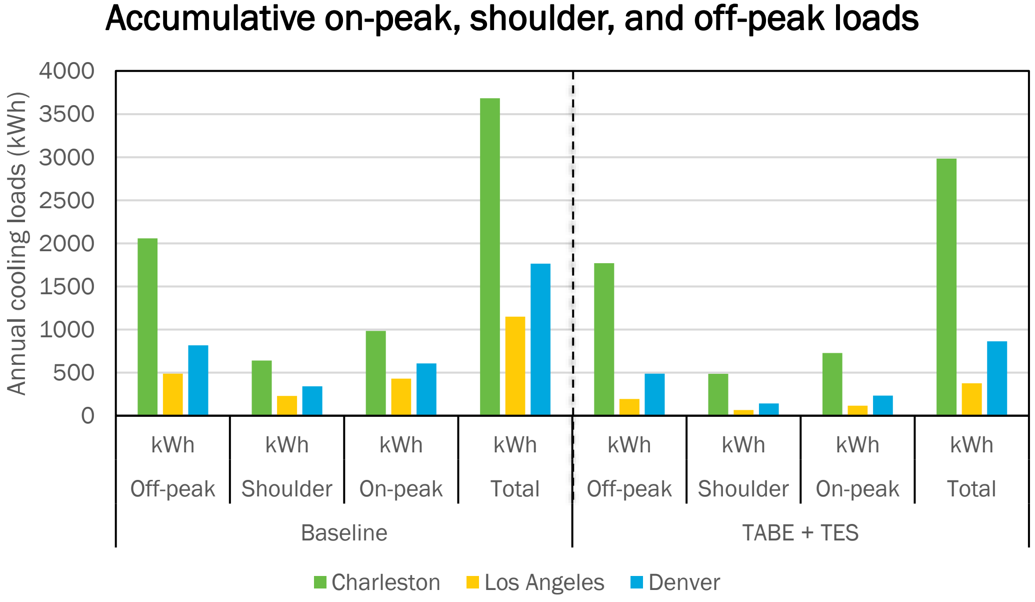
Beyond scope
Lifecycle testing PCMs energy storage by accelerated testing
2 organic and 2 inorganic samples cycled 10,000 times (4/19)

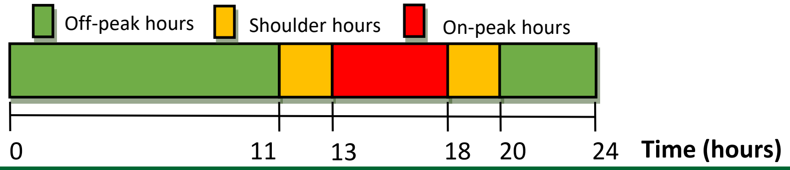
Organic PCMs maintain performance after 8,000 cycles

Progress: Modeling of TES integrated with TABE



- **Peak load shaving:**
  - Charleston, Los Angeles, and Denver have peak load shaving of 24%, 61%, and 73%.
- **HVAC electricity savings**
  - Charleston, Los Angeles, and Denver are 19%, 67%, and 51%.





TABE+TES performed very well in Los Angeles and Denver

Lessons learned: Year 1 empirical 3D FEM for PCM HX

- **Heat exchanger design**
  - Square fin geometry is easier to manufacture and more conservative than scaling circular fin geometry
  - Tube components more expensive than fin
  - Edge effects that reduce performance are smaller at larger scale
  - Longer tubes require careful consideration
  - Fin spacing (pitch) is more important than fin thickness
  - High-performance HX can be low mass and cost
- **Bulk materials testing**
  - HFMA more reliable than DSC for freezing temperature
  - DSC total enthalpy reasonable
- **Integration of TABE with TES**
  - Climates with large diurnal temperature swings will benefit by the technology more than others

Ongoing Work: Year 2 (5-gallon TES test-bed)

- **Fabricate and evaluate the performance of the TES systems at the laboratory**
  - Testbed construction underway
  - Models will be validated with experimental data

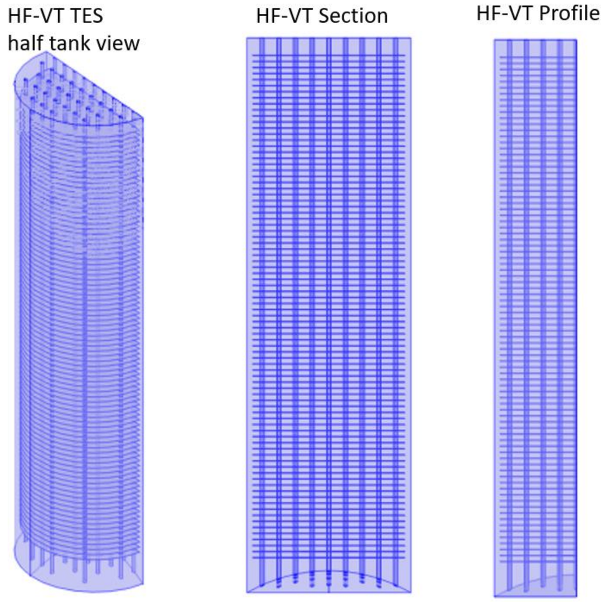
First Simple Heat Exchanger Prototype Built

Construction and DAQ 95% Complete

Ongoing Work: Year 2 (field site deployment)

Integrating TABE with TES for field evaluation

- Integration of TABE with TES and advanced controls to reduce HVAC loads
- Looking at inexpensive and common containers
- Requesting conformal heat exchanger manufacturing



NET facility at Charleston, SC.
Four wall panels in this NET facility are TABEs.

High performance, low-cost and scalable TES system will be constructed for field site evaluation

Future Work: Year 3 (Field scale validation and commercialization)

- **Field scale validation and energy performance of TABE+TES**
  - Field scale validation
    - Performance verification
    - Validate finite element models
  - Energy performance of TABE+TES
    - Building energy analysis for all climates
  - Develop and optimize control algorithm
- **Work with the industry to conduct economic and manufacturing analysis**
  - Identified one or two industry partners
    - Already talking with HX manufacture and PCM manufacturer.
  - Conduct manufacturing options analysis and economic analysis

Path identified for future success.

Publications and Intellectual Property

- **Conference proceedings or presentations**
  - Rendall, J., Shen, Z. Shrestha, S. Gehl, T., Atchley, J. "An Experimental Method to Determine The Contact Thermal Resistance Of PCM Materials Undergoing Large Volume Change", International Refrigeration and Air Conditioning Conference, 2022, Purdue University.
  - Rendall, J., Shen, Z., Shrestha, S., Gehl, T., "An Experimental Method to Determine the State of Charge of Phase Change Materials via Pressure Sensors in a Heat Flux Meter Apparatus", 35th International Thermal Conductivity Conference & 23rd International Thermal Expansion Symposium, 2022, University of Massachusetts
- **Journal publications (*under preparation*)**
  - Rendall, J., Shen, Z. Shrestha, S., Tamraparni, A., Hun, D., "Multiple-scale 3D FEM optimization of fin and tube heat exchanger for low-cost latent thermal energy storage"
  - Shen, Z., Rendall, J., Shrestha, S., Tamraparni, A., Hun, D., "Experimentally characterize the thermal properties of PCM: thermal conductivity, enthalpy, contact thermal resistance, and cyclic stability"
- **Patent applications**
  - Rendall, J., Shen, Z. Shrestha, S. Gehl, T., Atchley, J., Hun, D., "State of Charge Sensor for Phase Change Material Thermal Energy Storage" Provisional: U.S. 63/353,340 filed June 17, 2022, Nonprovisional (*under preparation*)

Thank you

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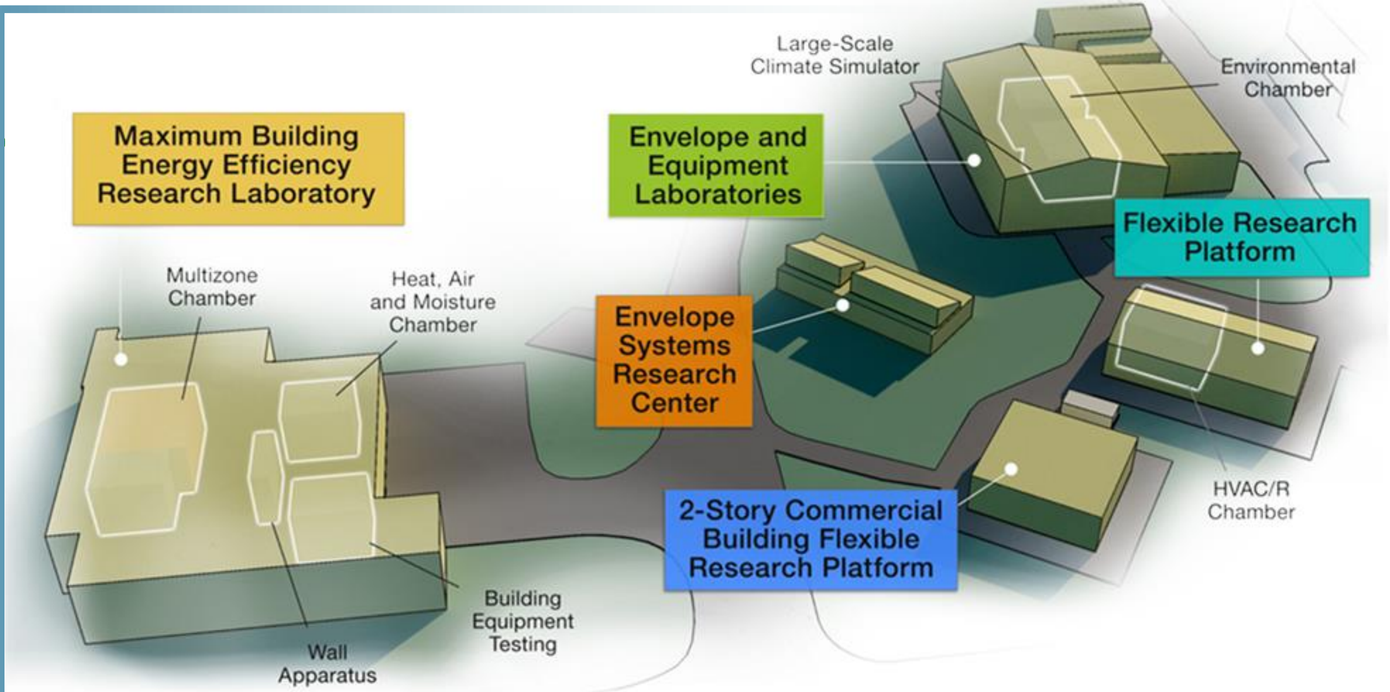

ORNL's Building Technologies Research and Integration Center (BTRIC) has supported DOE BTO since 1993. BTRIC is comprised of 60,000+ ft^2 of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free economy by 2050.

Scientific and Economic Results
236 publications in FY22
125 industry partners
54 university partners
13 R&D 100 awards
52 active CRADAs

BTRIC is a DOE-Designated National User Facility

REFERENCE SLIDES

Project Execution

	FY2023				FY2024				FY2025			
Planned budget	150K				450K				375K			
Spent budget	150K				200K							
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Select four PCMs, two for cooling applications and two for heating applications												
Evaluated the thermal properties of bulk quantity PCMs and selected two PCMs												
Completed the initial design of two small sizes (approximately 5 gal) TES tanks												
Completed the design of two ~5 gal TES tanks for laboratory evaluations and two large sizes for field validation.												
Finite element analysis showed 90% TES tank volume utilization, 75% of the stored latent energy discharged in three hours and 90% of the stored latent energy is discharged in four hours with $\Delta T <$ 10°F												
Current/Future Work												
Fabricated and instrumented two ~5 gal TES systems for laboratory evaluations												
Completed performance evaluation of the two ~5 gal TES systems at the laboratory												
Completed 200 thermal cycle tests on the ~5 gal TES systems												
Fabricated the two large TES systems and connected them with TABE at a NET facility												
Volumetric energy density of the PCM is maintained over 95% after 100 cycles.												
Assured at least 50% energy cost savings and > 50% peak cooling or heating load reduction from the integrated TES-TABE-controls.												
Whole building simulations predicted at least 50% energy cost savings and > 50% peak cooling and heating load reduction from the integrated TES-TABE-controls.												
Identified one or two industry partners that are interested in manufacturing TES systems and marketing them												
Conducted manufacturing options analysis to fabricate heat exchangers, TES tanks, and TES systems												

Year 1: Complete
Year 1: Go/No Go: Successful

Year 2: Slip in schedule due to manufacturing lead times

Year 3: Early start on manufacture identification

Team

Oak Ridge National Laboratory

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Joseph Rendall (Modeling and experiment design)
– Associate R&D Staff

Zhenglai Shen (Material characterization)
– Postdoctoral Research Associate

Achutha Tamraparni (Experimental evaluation)
– Postdoctoral Research Associate

Diana Hun (Group Leader)
– Senior R&D Staff

Tony Gehl (Testbed controls and DAQ setup)
– Technical Senior Staff

Islam Safir (Testbed construction)
– Technician

Danial Howard (Modeling)
– Graduate Student
Bredesen Center