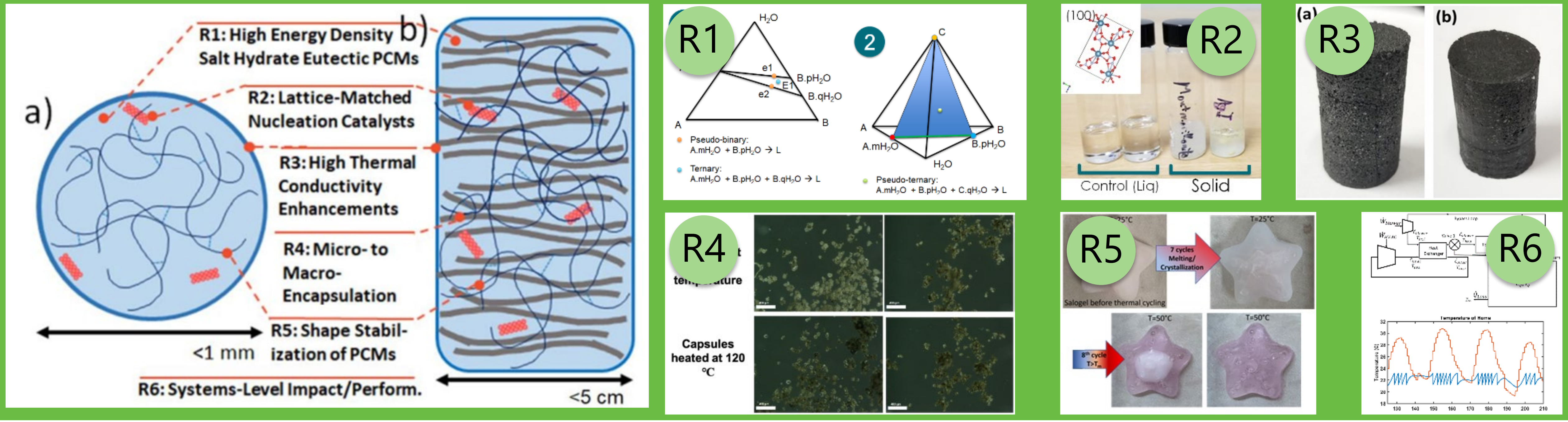
Salt Hydrate Eutectic Thermal Energy Storage for Building Thermal Regulation



Performing Organization(s): Texas A&M Engineering Experiment Station

PI Name and Title: Dr. Patrick Shamberger, Associate Prof.
PI Tel and/or Email: 979.458.1086 / patrick.shamberger@tamu.edu

Project Summary

Timeline:

Start date: 04/01/2020 (**NEW START**)
Planned end date: 07/31/2023
Key Upcoming Milestones:

1. Identify 3-4 salt hydrate eutectics in each of target ranges; 08/01/2021
2. Demonstrate decreased supercooling to <5 C in 2-5 eutectics; 08/01/2021
3. Demonstrate the general ability to shape stabilize nitrate and chloride salt hydrates (up to 100 cycles, >90 vol.% PCM; 02/01/2022
4. Demonstrate robust micro-encapsulation with >95 vol.% and <5% degradation over 10^3 melt cycles; 08/01/2022

Budget:

Total Project $ to Date:
- DOE: $466,749.
- Cost Share: $ 163,058.

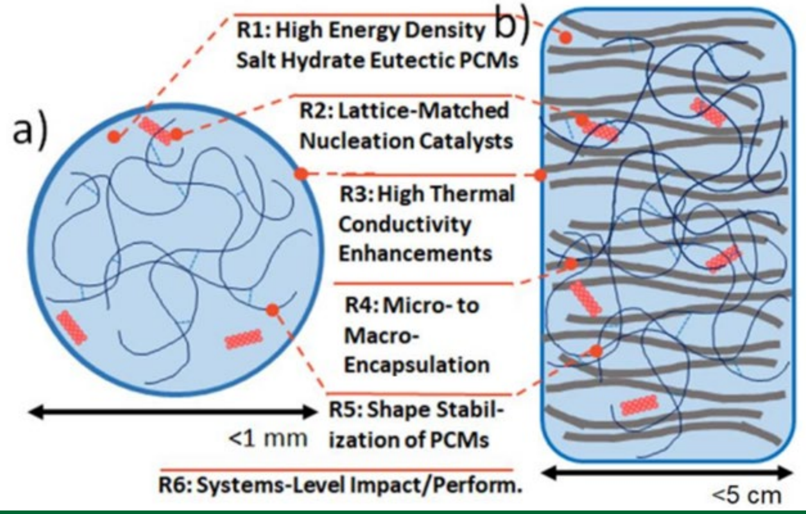
Total Project $:
- DOE: $1,546,556.
- Cost Share: $386,639.

Key Partners/Co-PI's: 4 Dept's, 6 PI's/Co-PI's

Dr. Choongho **YU** (TAMU, Mech Eng; R3).
Dr. Emily **PENTZER** (TAMU, Mat Sci Eng/Chem; R4).
Dr. Svetlana **SUKHISHVILI** (TAMU, Mat Sci Eng; R5).
Dr. Jonathan **FELTS** (TAMU, Mech Eng; R6).
Dr. Charles **CULP** (TAMU, Architecture; R6).

Project Outcome:

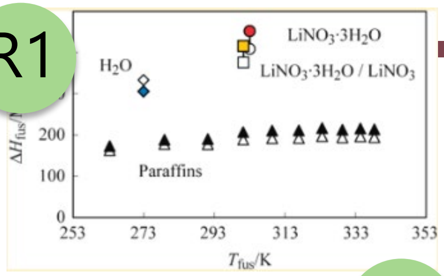
Low-cost, high energy-density, stable inorganic thermal energy storage material systems for integrating with HVAC: 5-25 ºC



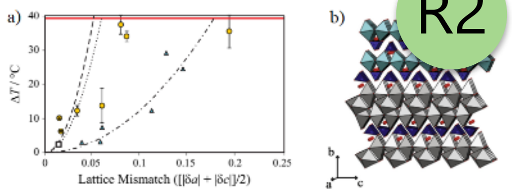
Team

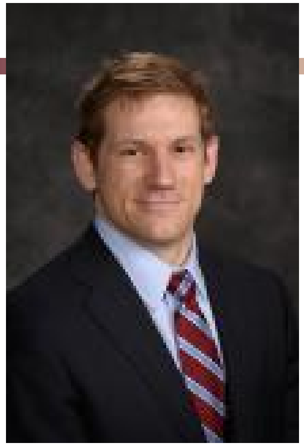
Salt Hydrate Eutectic Thermal Energy Storage for Building Thermal Regulation

R1



R2





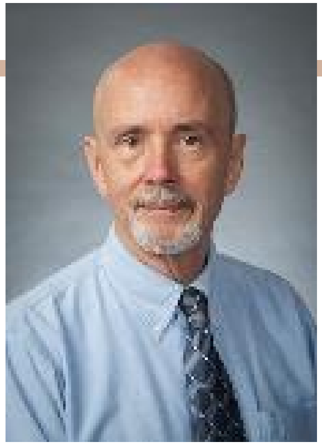
P. Shamberger **R1 / R2**

C. Yu **R3**

E. Pentzer **R4**

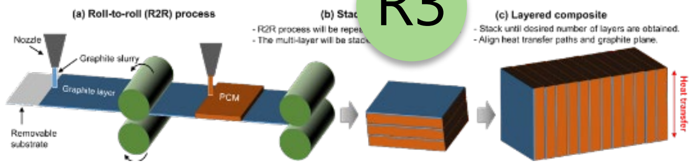
S. Sukhishvili **R5**

J. Felts **R6**

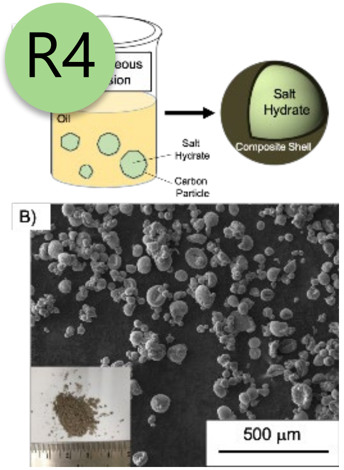


C. Culp **R6**

R3

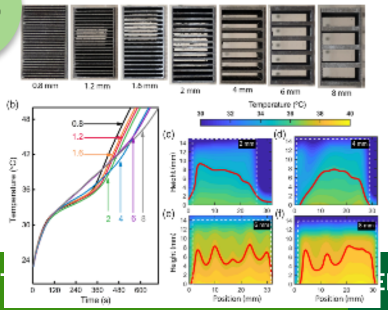


R4



R5

R6



Industrial Advisory Board:

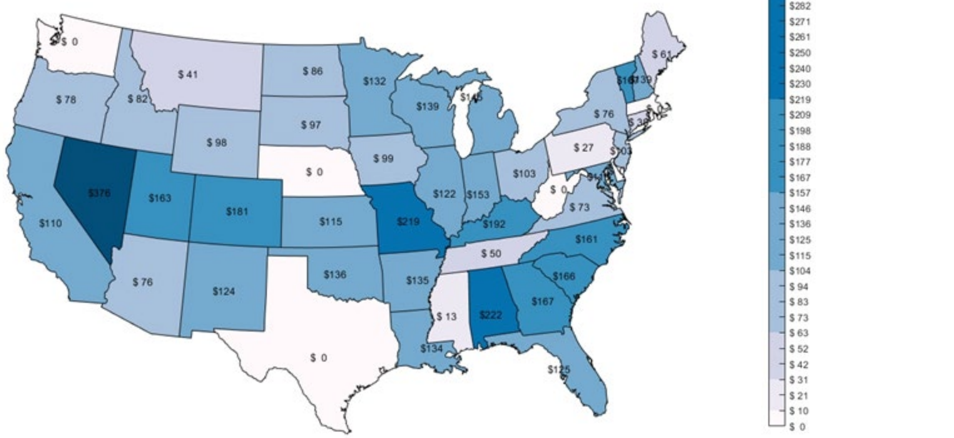
- NETenergy
- Viking Cold Solutions
- RGEES, LLC. // Akuratemp
- Thornton Tomasetti
- Dow Packaging
- Advanced Cooling Technologies
- Thermavant
- Latent Heat Sol'ns
- CALMAC
- CAVU group
- NREL
- ORNL

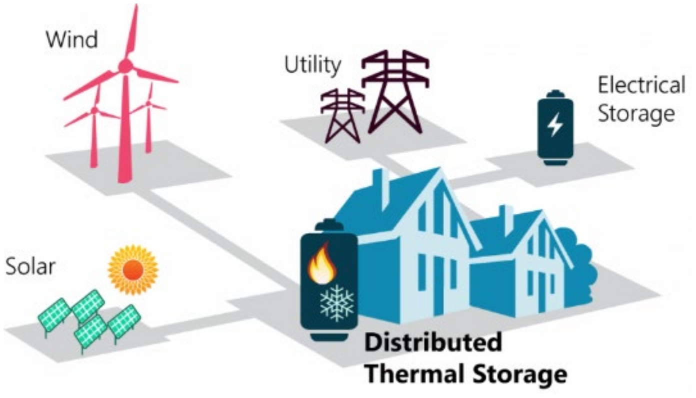
Challenge

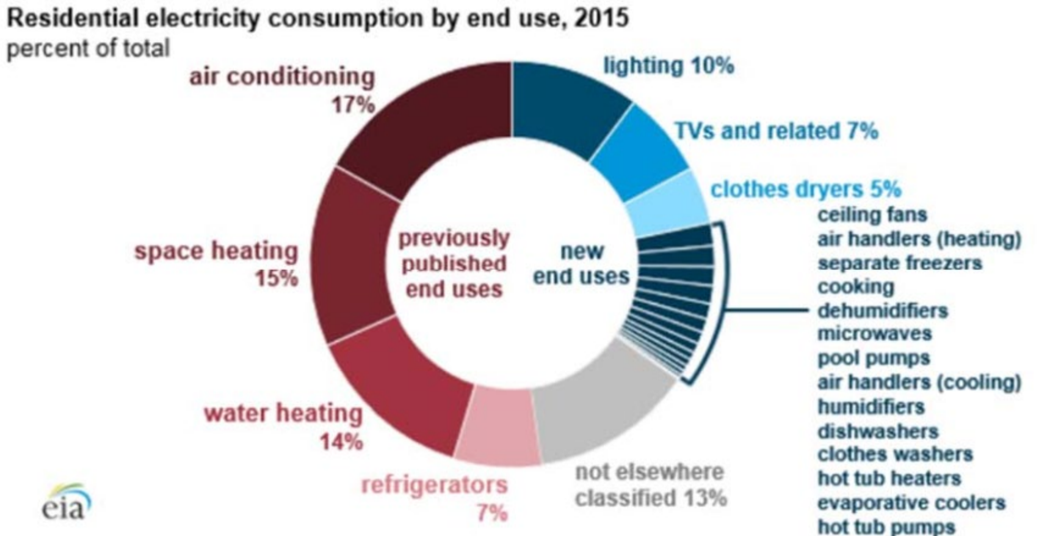
Problem Definition: Intermittent power generation and variable demand have resulted in variable electricity pricing schemes where peak prices are 5 to 40 ¢/kWh higher than off-peak prices. The largest single segment of residential electricity consumption (~30 to 35%) corresponds to building HVAC and commercial consumption is similar.

To capture this differential pricing, consumers require a low cost, dependable approach to displace use of HVAC to off-peak hours. Current technologies are limited by the capability of available thermal energy storage materials.

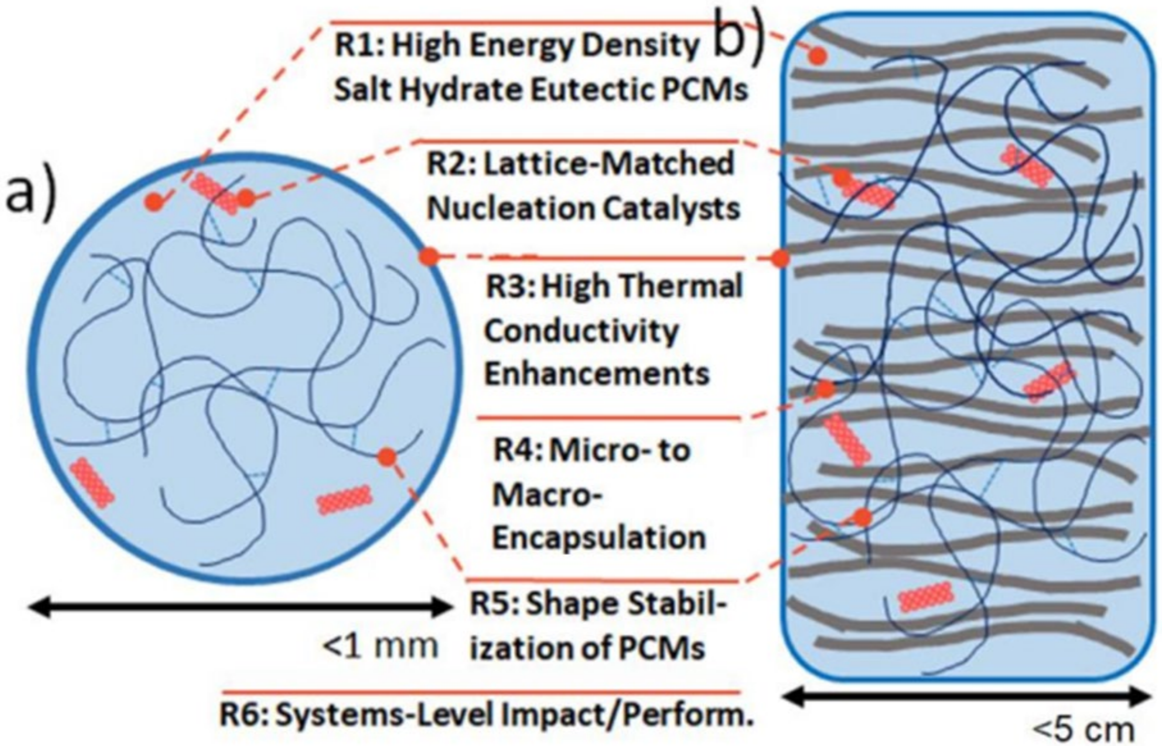
Avg. per capita potential savings for residential peak load shifting.

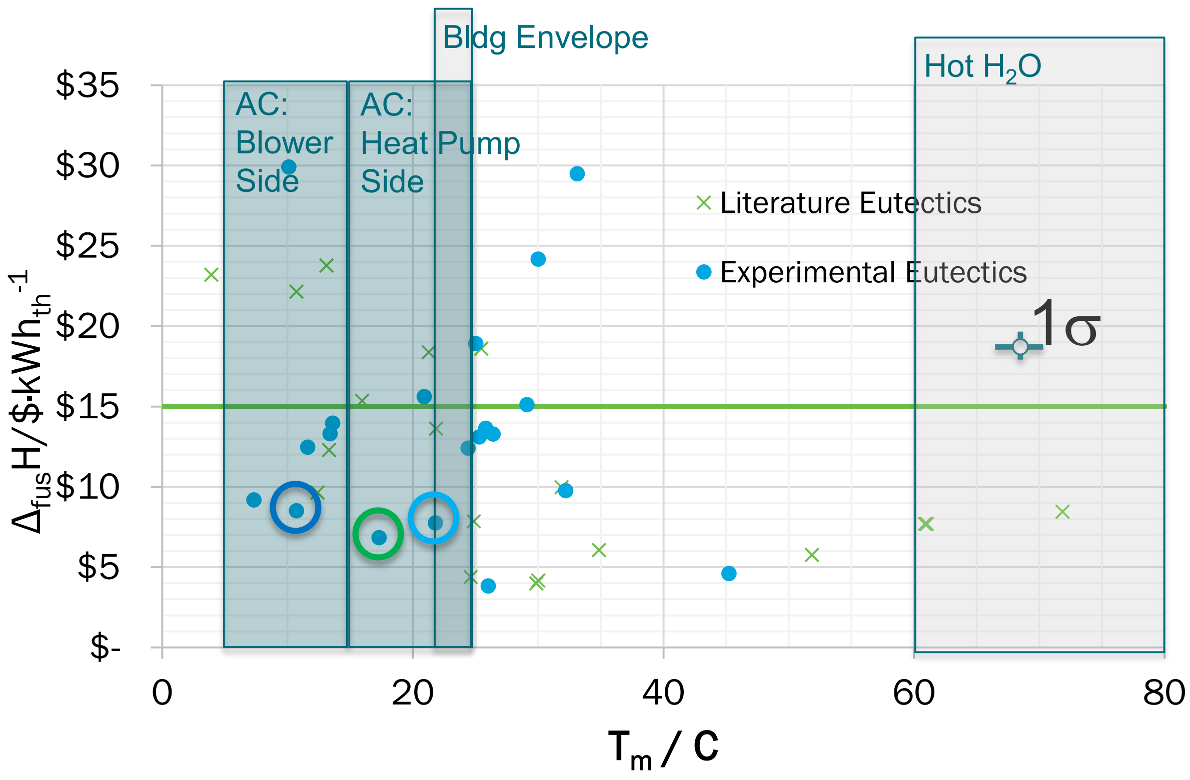




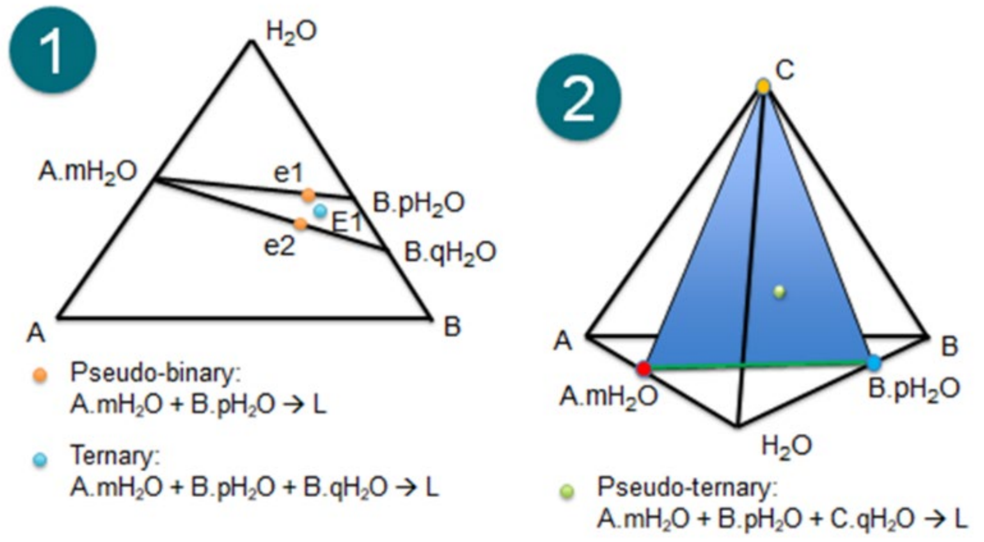


Approach + Takeaway

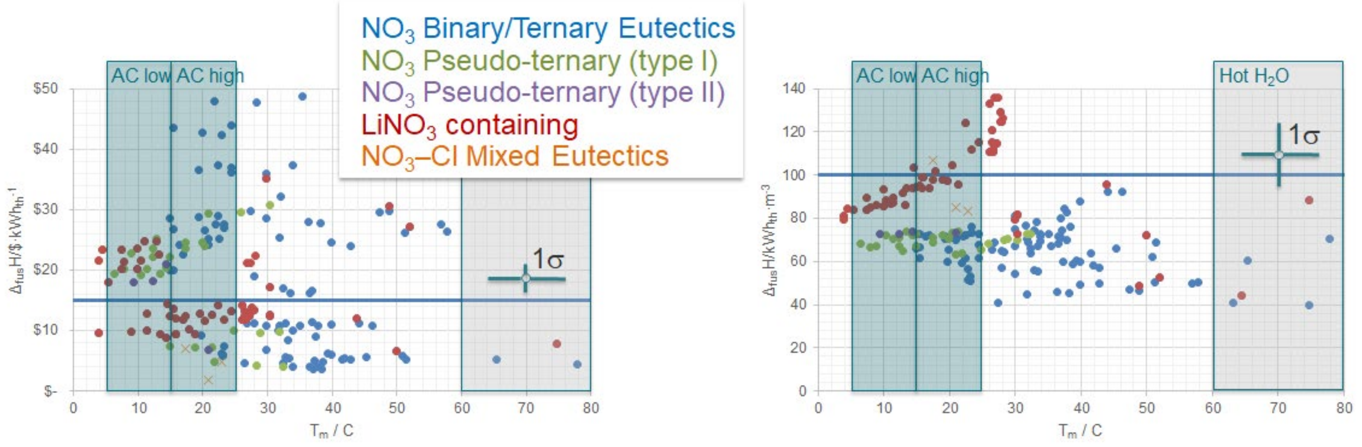




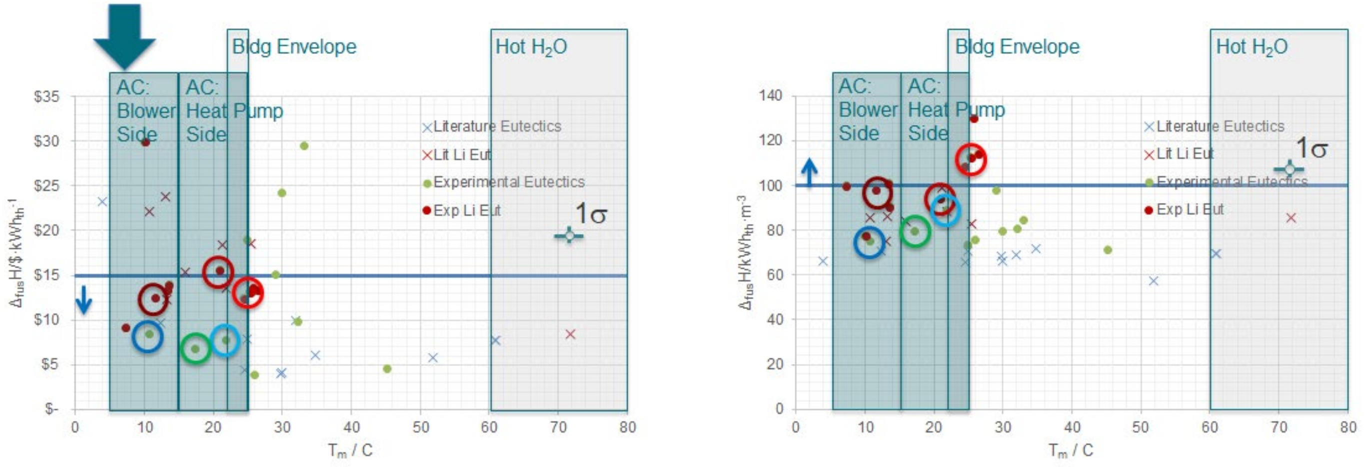
Progress: R1 Identify stable salt hydrate eutectics



Thermodynamic Predictions



Experimentally Measured



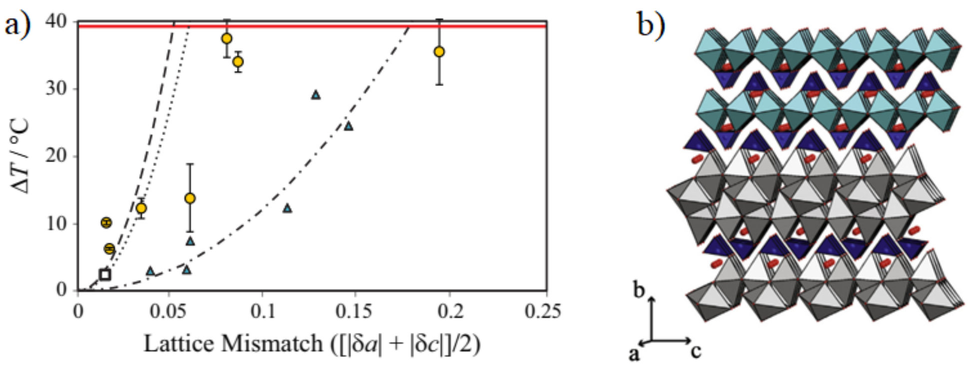
Accomplishments:

- Complete evaluation of pseudo-binary nitrate eutectics
- ID 2 to 4 compounds in both high T and low T ranges for HVAC: **subset of 3-4 eutectics <$10/kWh$_{th}$**

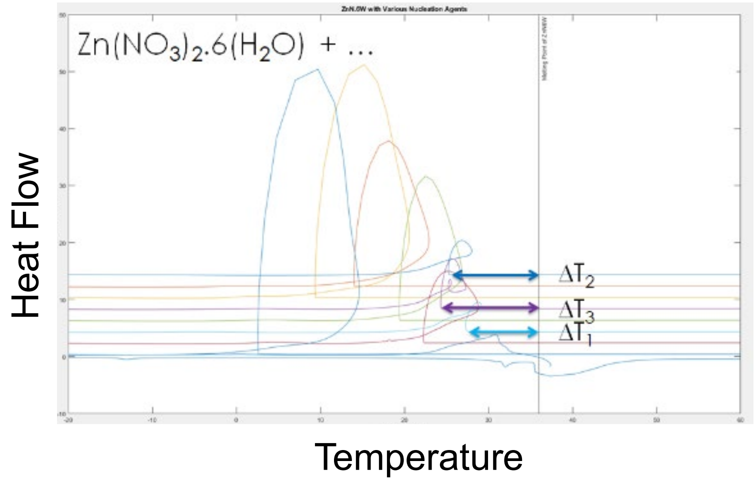
Next Steps:

- Evaluate mixed nitrate-chloride systems
- Move to deep eutectics to fine-tune eutectic temperature

Progress: R2 Decrease undercooling to <5 C



High throughput evaluation of Nucleation Agents (NA's)



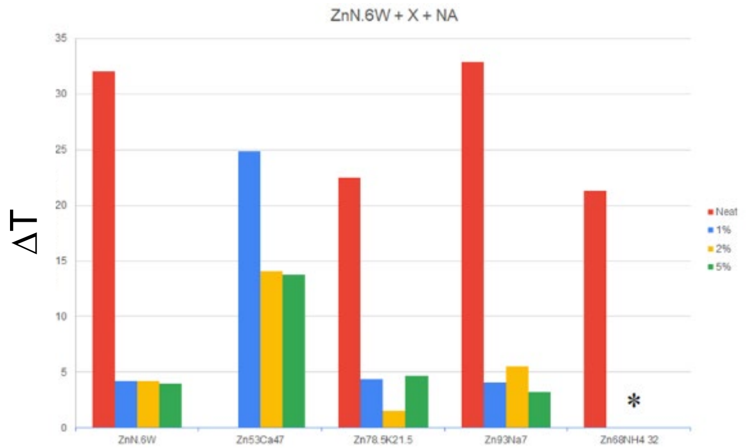
Accomplishments:

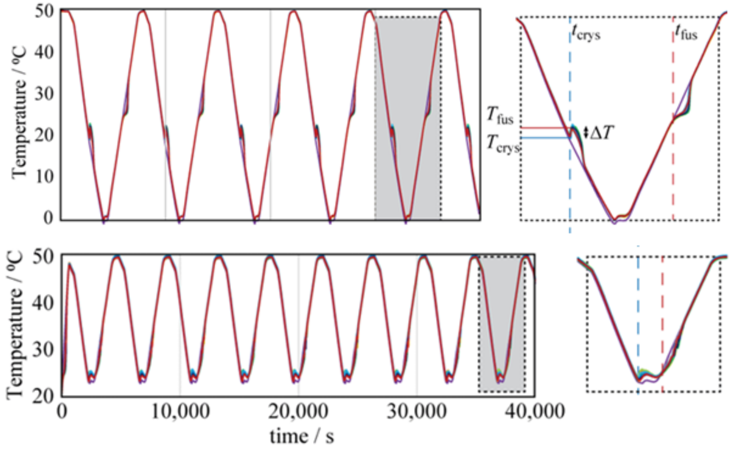
- Applied lattice-matching technique to different inorganic salt hydrates and salt hydrate eutectics.
- For eutectics of interest: ID'd appropriate NA's with ΔT < 5 C (at ~mL volumes).

Next Steps:

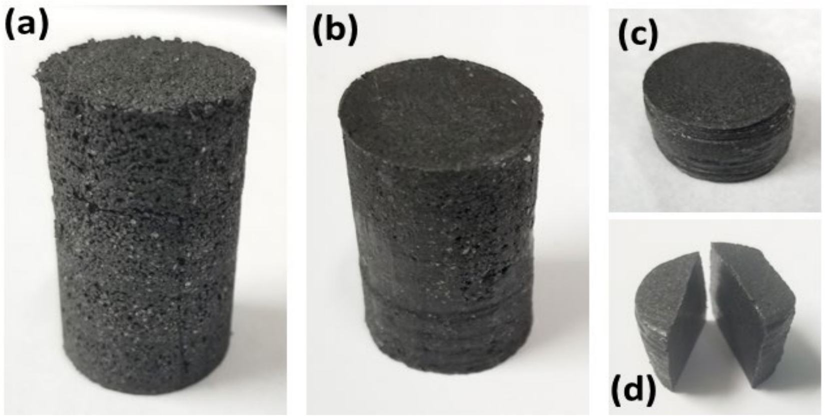
- Evaluate cycling, stability over time (degradation of NA activity).
- Continue to develop NA's for new eutectics.

Scaled Volume / Cycling



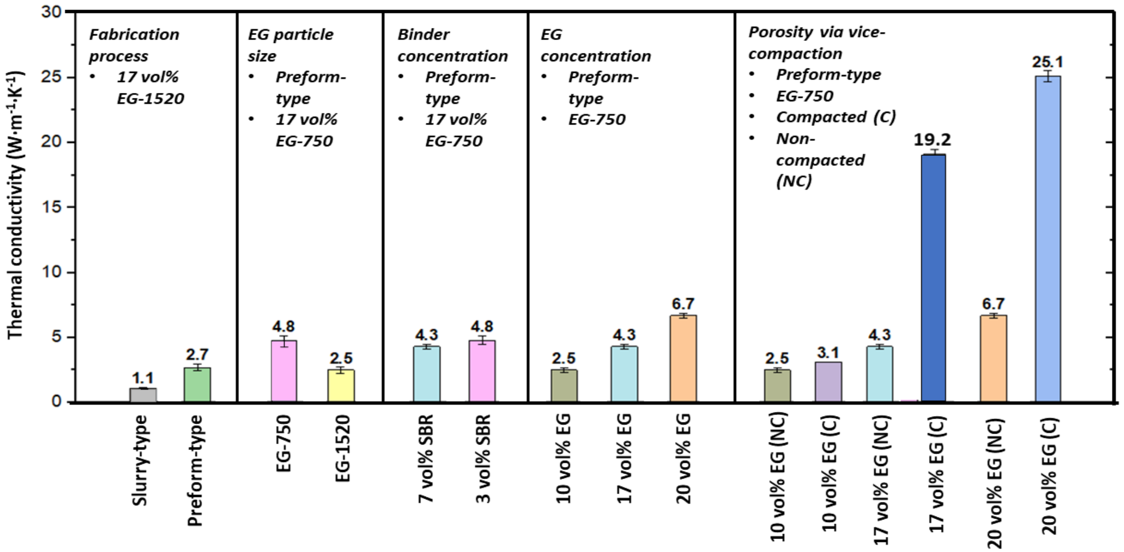


Progress: R3 Stable thermal conductivity enhancement



(a) Highly porous bare EG-750 matrix. (b) Paraffin infiltrated EG-750 matrix. (c) Compacted EG/paraffin wax composite. (d) Composite sectioned down the middle to analyze anisotropy of k-value.

Comparison of different processing techniques:



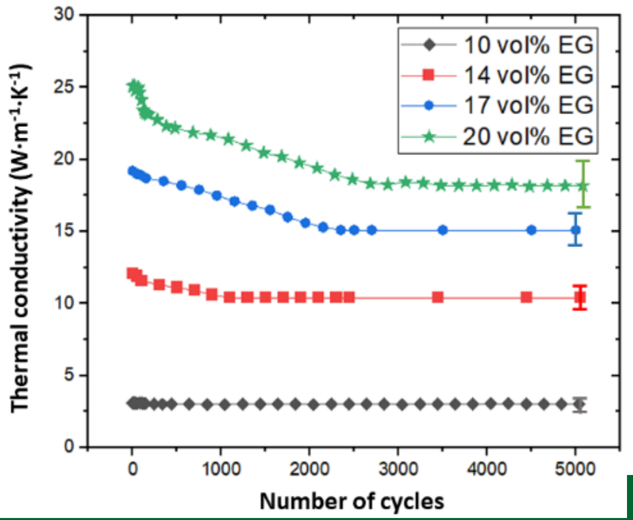
Accomplishments:

- Evaluate composite synthesis protocols and effect on latent heat/ thermal conductivity.
- Quantify degradation with cycling in different composites to >5k cycle.
- Demonstrated infiltration of salt hydrates in expanded graphite matrix

Next Steps:

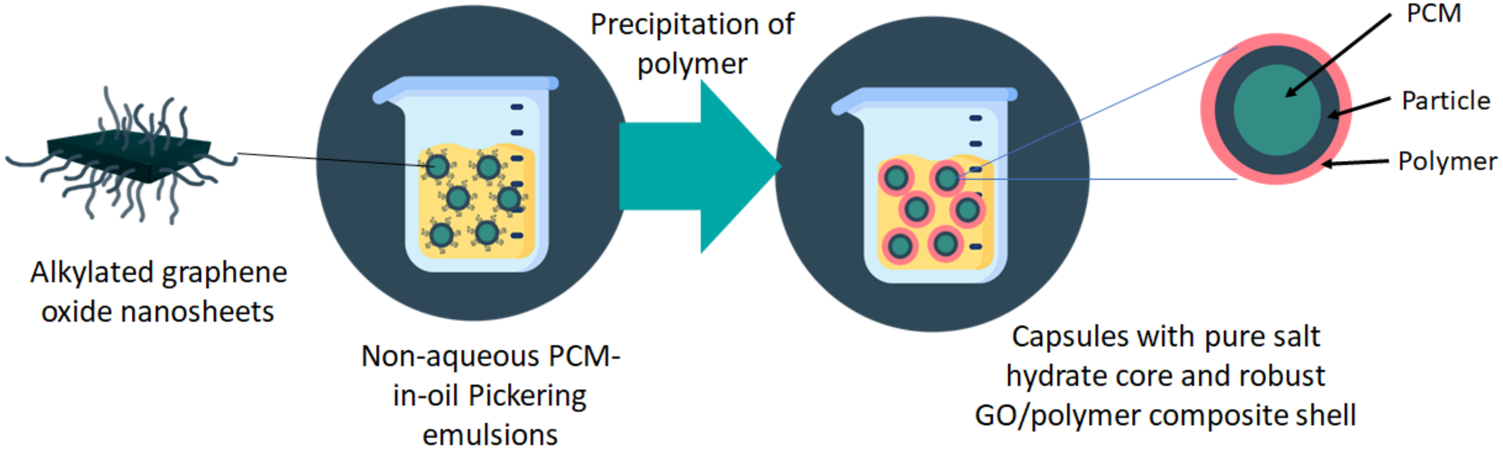
- Evaluate high thermal conductivity salt hydrate composites.

Long-term cycling behavior:

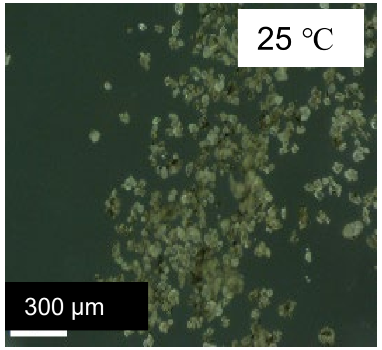


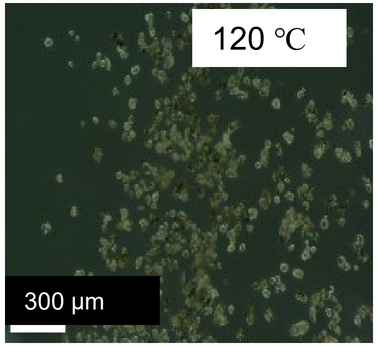
Progress: R4 Microencapsulation of Salt Hydrate Eutectics

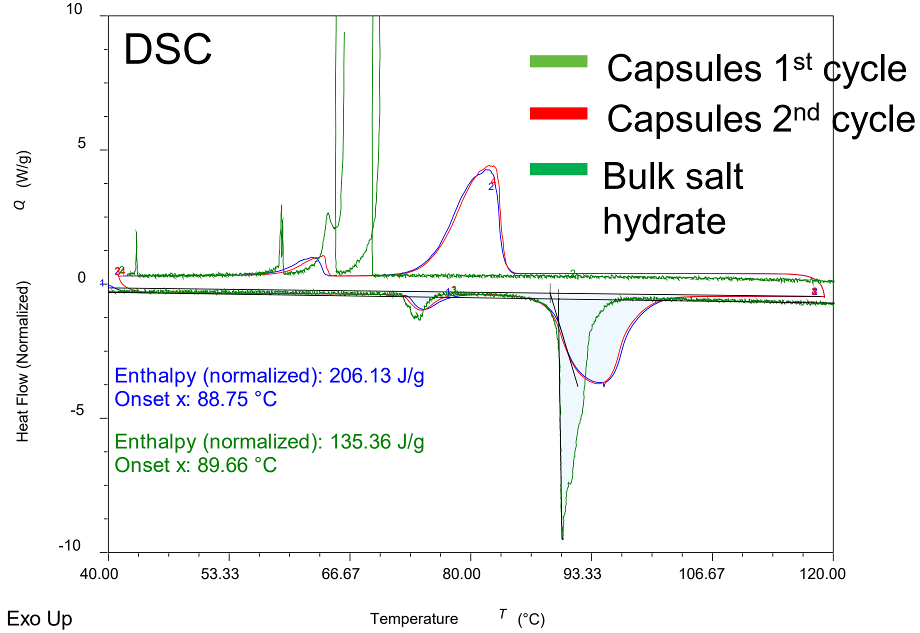
Approach:



$Mg(NO_3)_2.6(H_2O)$ Capsules







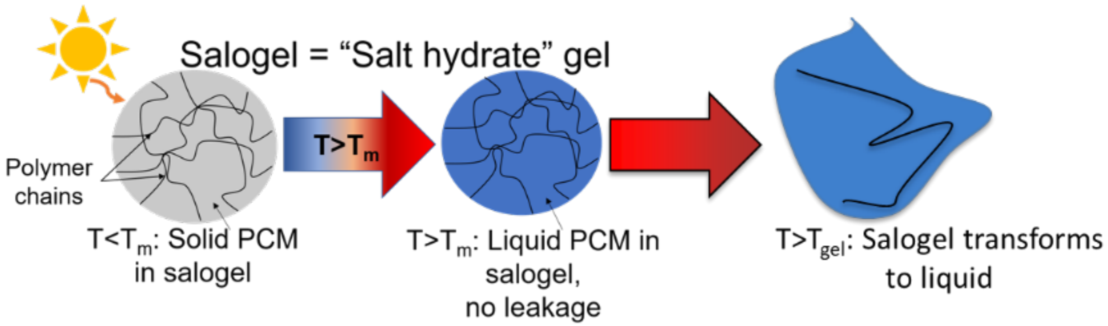
Accomplishments:

- Development of PCM-agnostic approach to microencapsulation based on Pickering emulsions
- Applicable to different polymer coatings as well
- Stable for small numbers of cycles
- Cooperative nucleation effect (decrease undercooling)

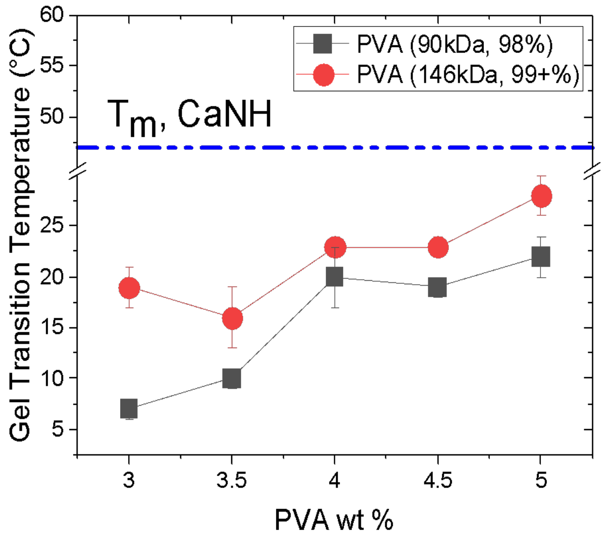
Next Steps:

- Evaluate aging/stability with:
  - Cycling
  - Different environmental relative humidities

Progress: R5 Decrease undercooling to <5 C

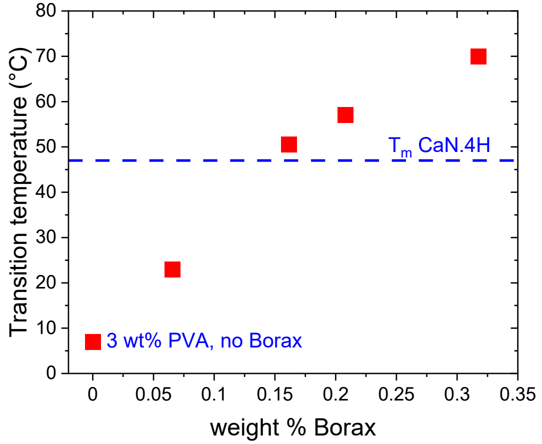


PVA-CaNH



PVA-borax-CaNH

3 wt% PVA (90 kDa, 98% degree of hydrolysis), borax as a crosslinker)



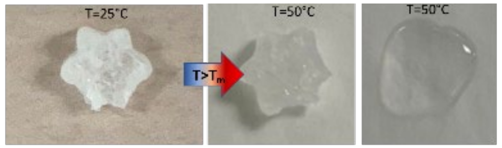
Accomplishments:

- Physical gels using hydrogen-bonded-network forming polymers – poly(vinyl alcohol) (PVA).
- Addition of small amounts of borax raises transition temperature of salogels above Tm of a PCM
- Increase in PH further strengthens salolgels

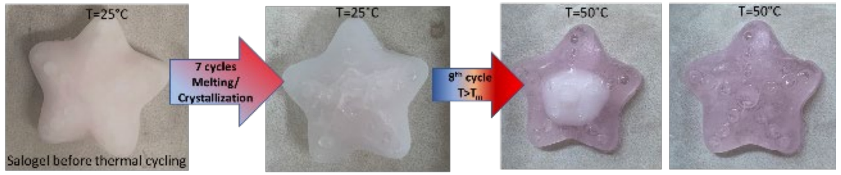
Next Steps:

- Apply this technique to salt hydrate eutectics

Shape Stabilization with minimal impact on latent heat

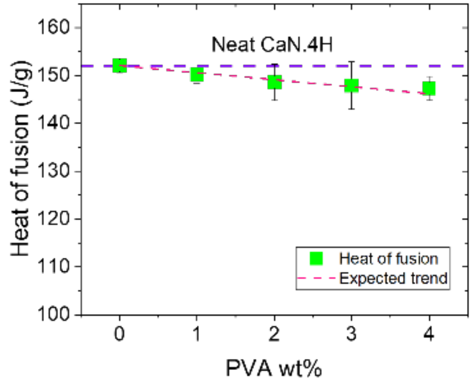


3 wt% PVA-0.32 wt% borax-CaN.4H salogel



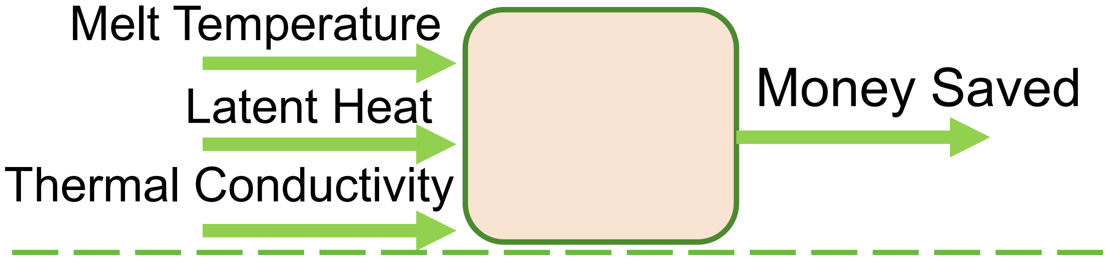
PVA-borax-CaNH systems after 7th cycle of melting/ crystallization and during melting in the 8th cycle

PVA-CaNH

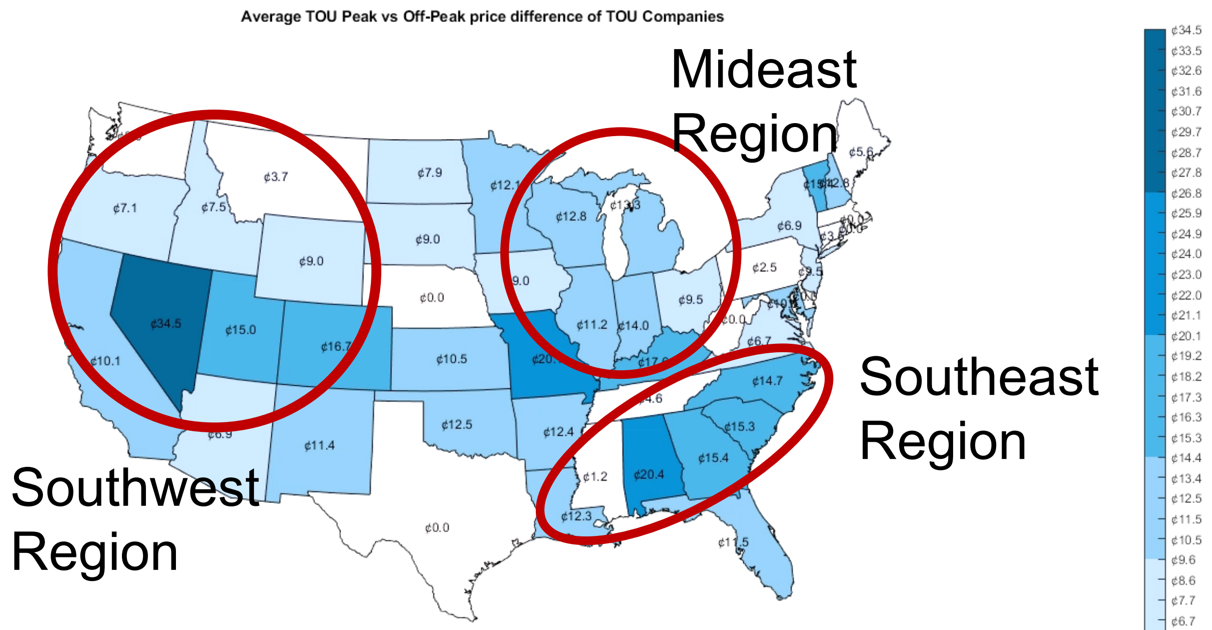


Progress: R6 Transient Thermal Modeling

Provide Engineering and Economic Requirements to the Materials Development Team

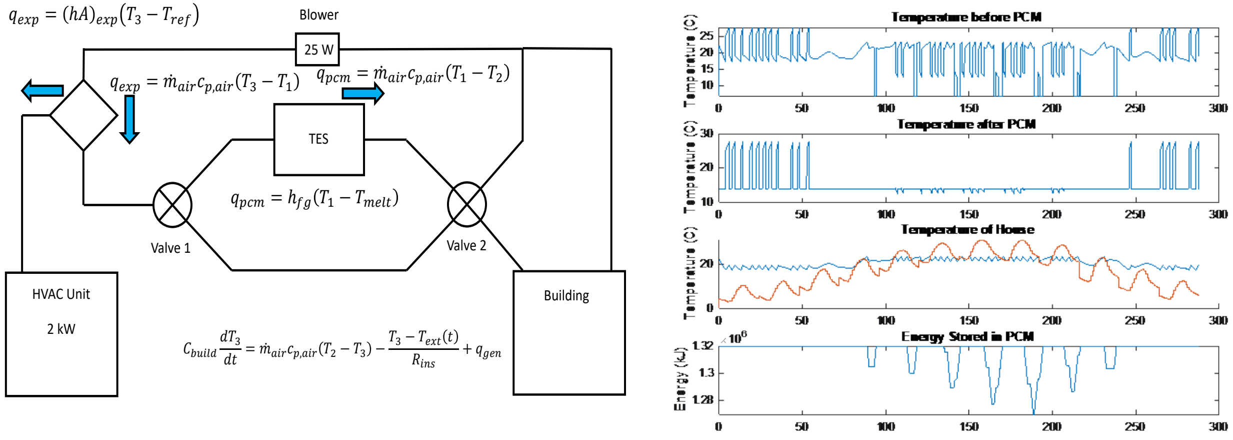


Regional Peak Load Shifting Cost Savings Map



Note: States with zero difference are incomplete data sets

Lumped Thermal Modeling of PCM Architectures



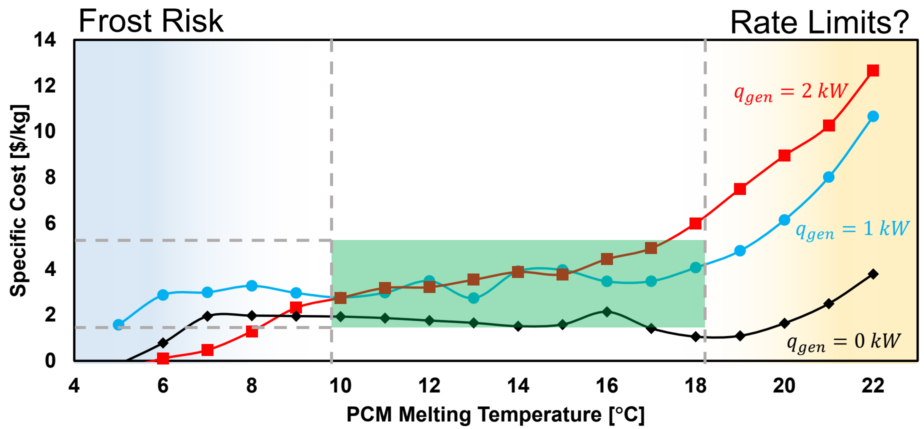
$q_{exp} = (hA)_{exp}(T_3 - T_{ref})$

$q_{exp} = \dot{m}_{air} c_{p,air}(T_3 - T_1)$

$q_{pcm} = \dot{m}_{air} c_{p,air}(T_1 - T_2)$

$q_{pcm} = h_{fg}(T_1 - T_{melt})$

$C_{build}\frac{dT_3}{dt} = \dot{m}_{air} c_{p,air}(T_2 - T_3) - \frac{T_3 - T_{ext}(t)}{R_{ins}} + q_{gen}$



Impact

1) Towards DOE ***Energy Storage Grand Challenge roadmap goal*** of $0.05/kWh levelized cost of storage for long-duration stationary applications, a 90% reduction from 2020 baseline costs by 2030.

Table 1. Levelized Cost of Thermal Energy Storage

t	Cost of Storage Media		
(yrs)	$5/kWh$_{th}$	$10/kWh$_{th}$	$15/kWh$_{th}$
10	$ 0.019	$ 0.037	$ 0.056
20	$ 0.013	$ 0.025	$ 0.038
30	$ 0.011	$ 0.022	$ 0.033

$$LCOS = \frac{\sum (Capital_t + O\&M_t + Fuel_t) \cdot (1+r)^{-t}}{\sum MWh_t \cdot (1+r)^{-t}}$$

- $r = 8\%$
- $t = 10$ to 30 yr
- *Energy discharge/yr = cycles/yr × utilization*
- *Cycles/yr = 80*
- ***Utilization = 50%***

2) Towards 1-2 yr simply payback cost for installed thermal energy storage.

Table 2. Simple payback (in yrs) assuming utilization of 0.5

Δ	Cost of Proposed Technology		
$/kWh	$5/kWh$_{th}$	$10/kWh$_{th}$	$15/kWh$_{th}$
$0.10	1.3	2.5	3.8
$0.20	0.6	1.3	1.9
$0.30	0.4	0.8	1.3

$$\begin{bmatrix}\text{Simple}\\\text{Payback}\\\text{(Yr)}\end{bmatrix} = \begin{bmatrix}\text{Incremental Cost}\\\text{of Proposed Tech}\\(\$/\text{kWh}_{\text{th}})\end{bmatrix} \Big/ \begin{bmatrix}\text{Cost}\\\text{Savings}\\(\$/\text{kWh/Yr})\end{bmatrix}$$

$$\begin{bmatrix}\text{Cost}\\\text{Savings}\\(\$/\text{kWh/Yr})\end{bmatrix} = \begin{bmatrix}\text{Savings from}\\\text{a single cycle}\\(\$/\text{kWh}_{\text{displaced}})\end{bmatrix} \times \begin{bmatrix}\text{Number of}\\\text{cycles}\\\text{(cycles/yr)}\end{bmatrix} \times \begin{bmatrix}\text{Utilization}\\\left(\frac{\text{kWh}_{\text{displaced}}}{\text{kWh}_{\text{installed}}}\right)\end{bmatrix}$$

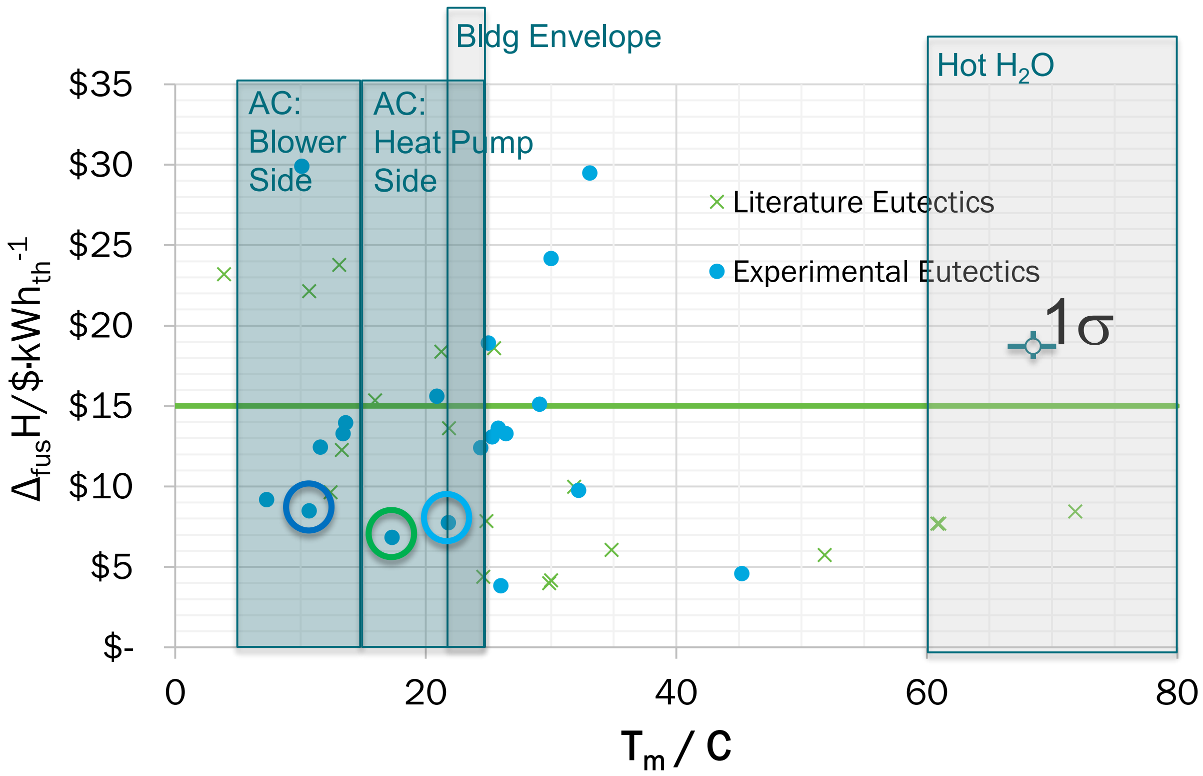
Stakeholder Engagement

This is an early stage project (just completed yr 1).

Industrial Advisory Board:

- NETenergy
- Viking Cold Solutions
- RGEES, LLC. // Akuratemp
- Thornton Tomasetti
- Dow Packaging
- Advanced Cooling Technologies
- Thermavant
- Latent Heat Sol'ns
- CALMAC
- CAVU group
- NREL
- ORNL

Remaining Project Work



Ultimate Success: A suite of robust low-cost materials solutions spanning 5 to 25 C

R1 **EVALUATE ADDITIONAL EUTECTICS:**

- Displace costly components
- Fine-tune eutectic temperature

R2 **STABILITY/RATE-DEPENDENT SOLIDIFICATION**

- Focus on eutectics of interest

R3 **HIGH THERMAL CONDUCTIVITY COMPOSITES**

- Translate results to salt hydrate systems

R4 **MICROENCAPSULATION**

- Demonstrate generality of technique
- Test robustness of microencapsulations

R5 **SHAPE STABILIZATION**

- Translate initial results to eutectics of interest

R6 **COMPONENT-LEVEL MODELING**

- Optimize conductivity/latent heat trade offs for particular applications

Thank You

Performing Organization(s): Texas A&M Engineering Experiment Station
PI Name and Title: Dr. Patrick Shamberger, Associate Prof.
PI Tel and/or Email: 979.458.1086 / patrick.shamberger@tamu.edu

REFERENCE SLIDES

Project Budget

Project Budget:

Variances: 4 mo. No-Cost Extension (04/2021 – 07/2021) to account for COVID-related delays to project start

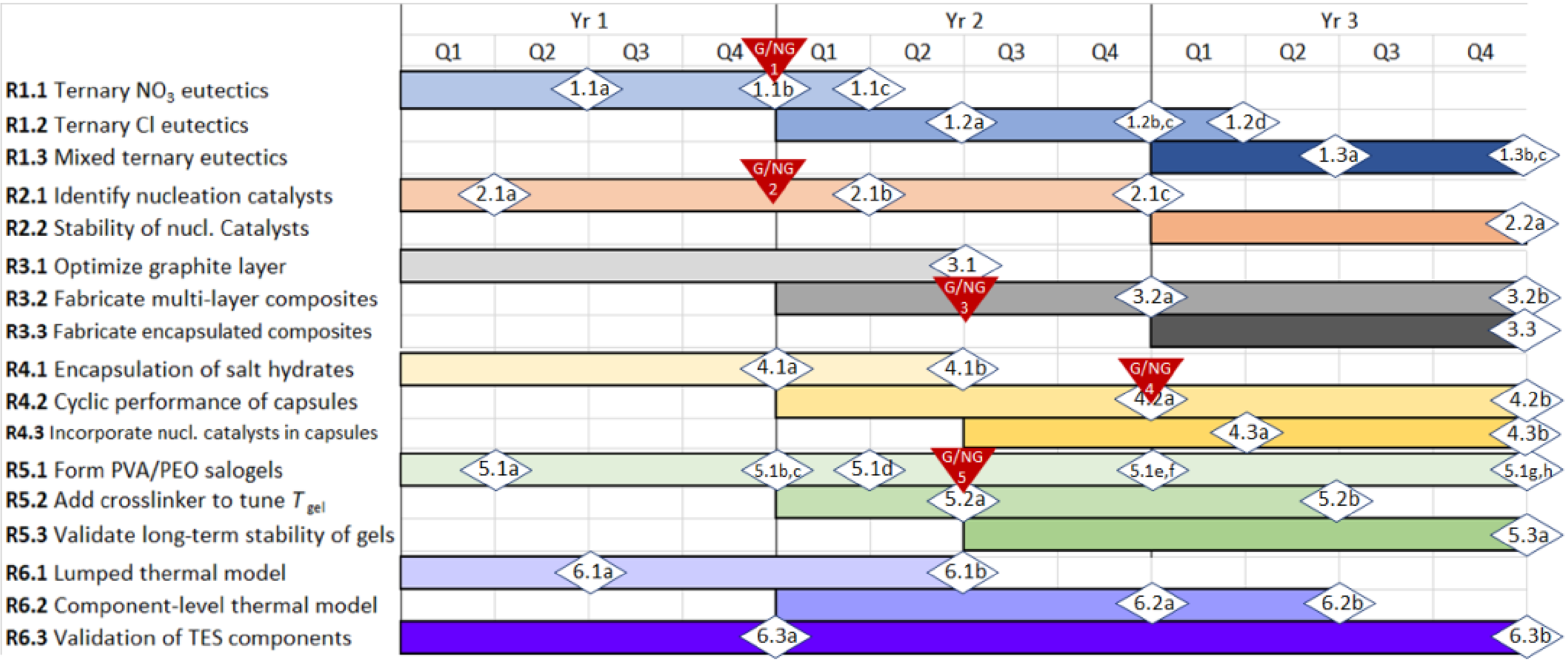
Cost to Date: $466,749 (DOE)/ **$163,058** (cost-share)

Additional Funding: N/A

Budget History					
04/01/2020 – FY 2020 (past)		FY 2021 (current)		FY 2022 – 07/31/2023 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$466,749.	$163,058.	$533,090.	$110,212.	$546,717.	$113,369.

Project Plan and Schedule

3.7 Gantt Chart



Start date: 04/01/2020 (**NEW START**)

Planned end date: 07/31/2023

(4 mo. no-cost extension at end of yr 1 related to slow-start due to limitations in lab associated with COVID protocols.)

G/NG 1	Yr1, Q4	Are the posed PCM discovery approaches converging on acceptable PCMs? Identify eutectic nitrate PCMs which maintain high volumetric density (>80 kWh/m^3), while reducing cost to <$10/kWh.
G/NG 2	Yr1, Q4	Is undercooling generally surmountable in salt hydrate PCMs through ID of appropriate nucleation catalysts? Demonstrate DT < 5 C in (a) ~2 to 5 nitrate hydrate eutectic phases, and (b) ~2 to 5 nitrate chloride eutectic phases of interest.
G/NG 3	Yr2, Q2	Can lamellar graphitic PCM composites increase directional thermal transport, while sustaining repeated melt cycles? Demonstrate effective thermal conductivity of >1 $W{\cdot}m^{-1}{\cdot}K^{-1}$ for >90 vol.% PCM, and survivability for >1000 melt/freeze cycles with minimal degradation of thermal properties.
G/NG 4	Yr2, Q4	Are capsules of salt hydrates with less than 10 vol% shell stable to extended aging? Microencapsulation of target salt hydrate phase with >95% yield, and <5% degradation of DH_{fus} over extended aging (up to ~3 to 6 mo.).
G/NG 5	Yr2, Q2	Are polymer-based salogels capable of shape stabilization for both nitrate and chloride hydrate eutectics? Demonstrate thermo-reversible gelation in salogel consisting of >90 vol.% PCM for proto-typical nitrate hydrate eutectic and chloride hydrate eutectics.