Bio-based phase change materials (PCMs) for thermal energy storage

University of Virginia, Tandem Repeat, Georgia Institute of Technology
Patrick E. Hopkins, Professor of Mechanical and Aerospace Engineering
Tel: 434.982.6005; Email: phopkins@virginia.edu

University of Virginia TANDEM REPEAT Georgia Tech

Project Summary

Timeline:

Start date: 4/1/2020

Planned end date: 5/31/2022

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

1. Developed novel bio-based PCM based on squid ring teeth (SRT) with room temperature energy storage and thermal conductivity switching capabilities
2. Scaled green, carbon neutral manufacturing of SRT PCM
3. Developed new thermometry tool to measure thermal conductivity and energy storage density of thin film PCMs

Key Partners:

Dr. Ben Allen	Tandem Repeat
Prof. Shannon Yee	Georgia Tech
Prof. Melik Demirel	Penn State

Budget:

Total Project $ to Date:

- DOE: $963,221.25
- Cost Share: $233,053

Total Project $:

- DOE: $1,750,000
- Cost Share: $458,333

Project Outcome: Assess feasibility of a new room temperature bio-based phase change material to establish a new SOA for energy storage density at room temperature, while also providing the ability to dynamically switch its thermal conductivity to record setting values. This PCM, derived from squid ring teeth protein, will be self healing, non-toxic and manufactured with a carbon circular/neutral process.

Team

Prof. Patrick Hopkins
PCM thermal property measurements

Dr. Ben Allen
Protein-based PCM manufacturing and scaling

Prof. Shannon Yee
Thermal system design

Challenge 1: Low *T* materials with high energy storage density

- Low temperature, non-volatile/toxic PCMs have relatively low energy storage capacity
- Lead to low figures of merit (FOM)

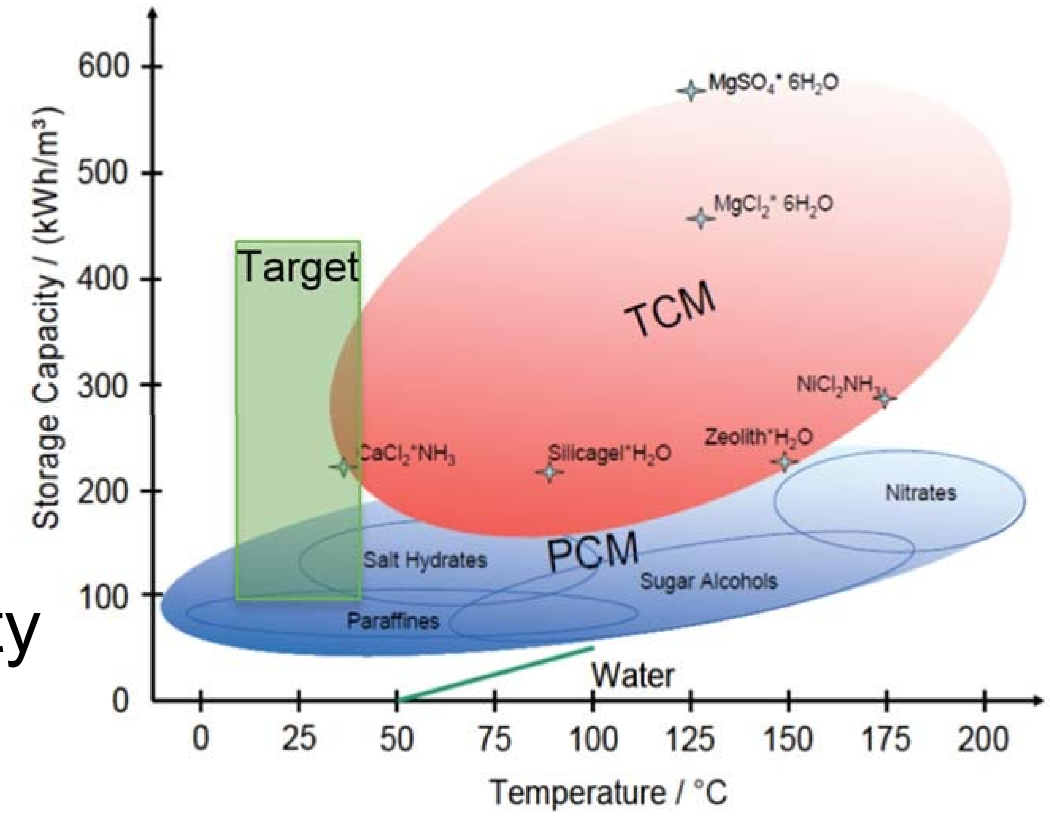
$$\mathrm{FOM} \propto E = \sqrt{\kappa C}$$

Thermal effusivity (E)   Thermal conductivity (κ)   Heat capacity (C)

Int. J. Heat Mass Trans. **43**, 2245 (2000)

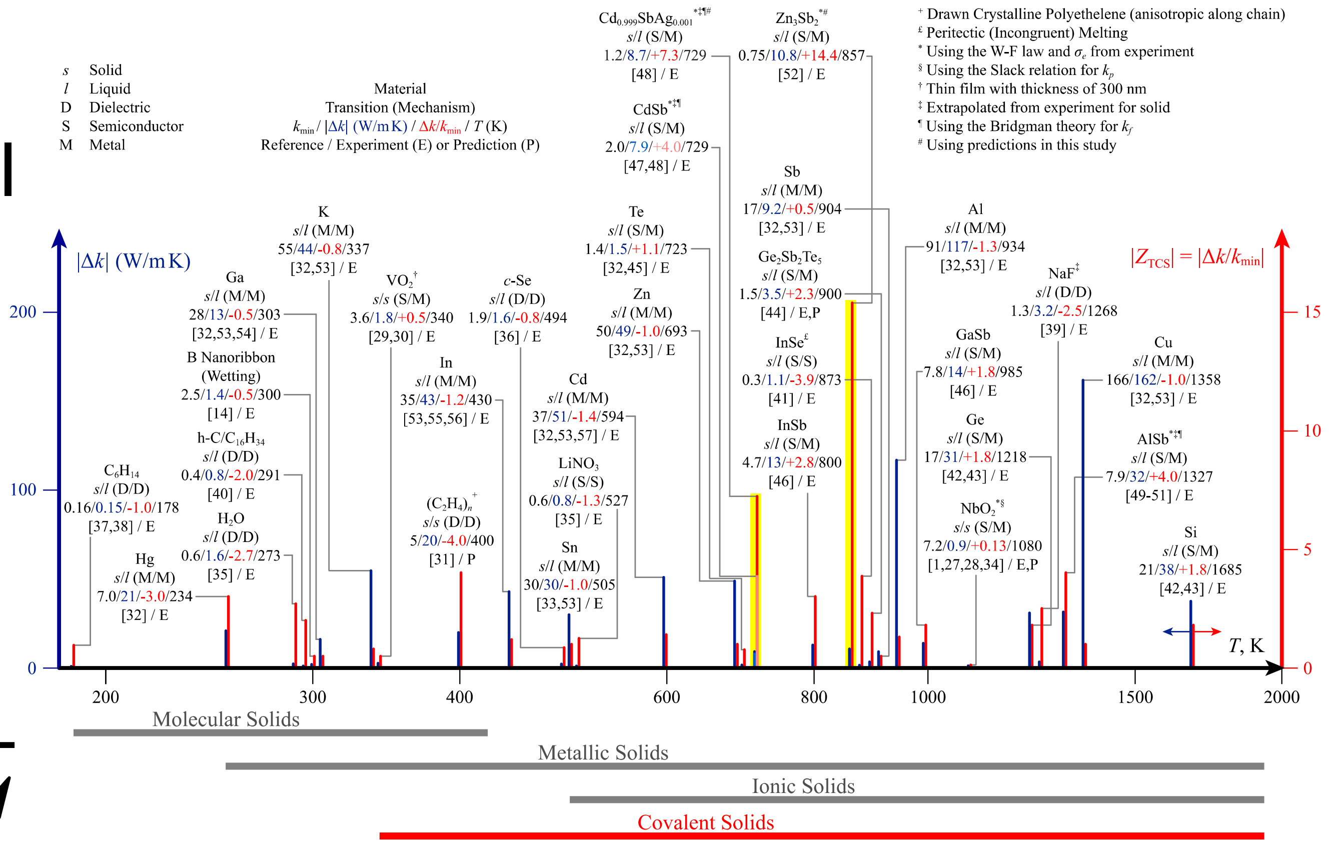
J. Heat Trans. **138**, 024502 (2015)

BTO targets



Challenge 2: Materials with “on demand” thermal conductivity

- Charging/discharging rate and heat flux in/out based on thermal conductivity
- Can we selectively control thermal conductivity during charge/discharge and storage states



$$\mathrm{FOM} \propto E = \sqrt{\kappa C}$$

Phys. Rev. B **94**, 155203 (2016)

Grand challenges

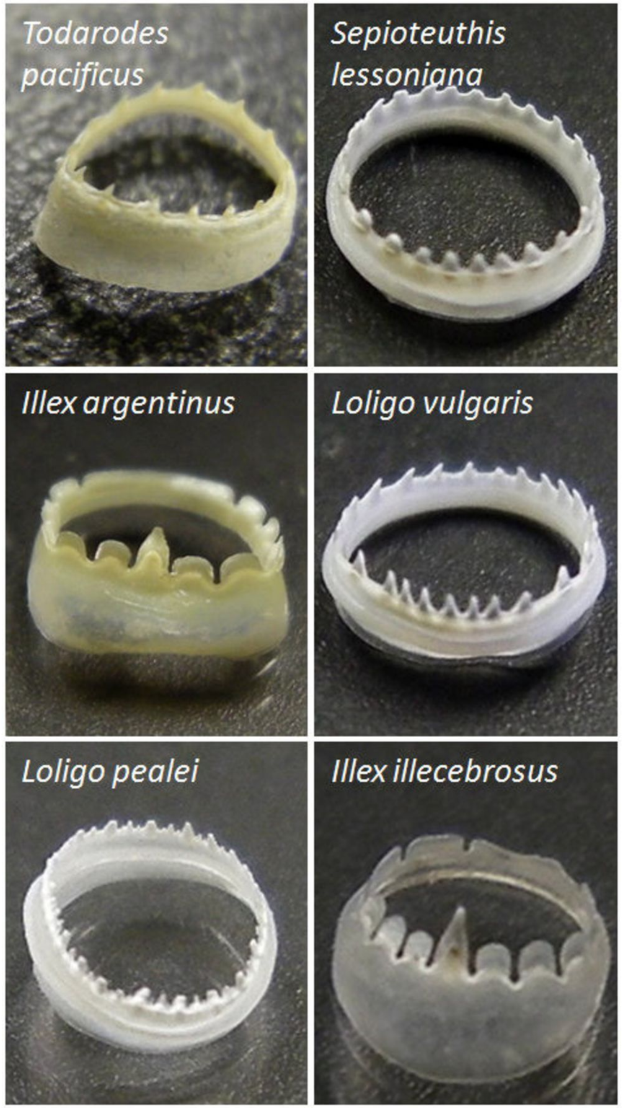
- **Thermal properties**: high energy storage density (> 100 kWh/m^3), switchable thermal conductivity at low T (>5X)

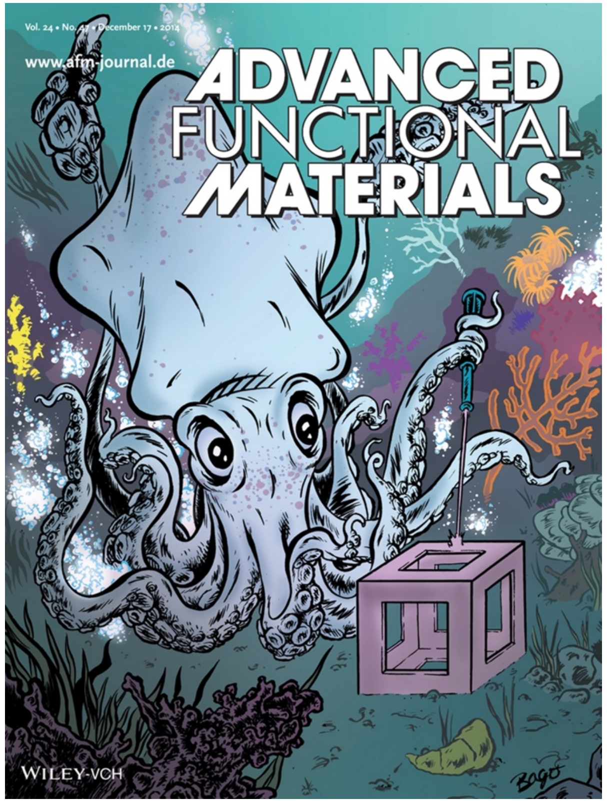
- **Manufacturing properties**: scalable to < $15/kWhr at scale

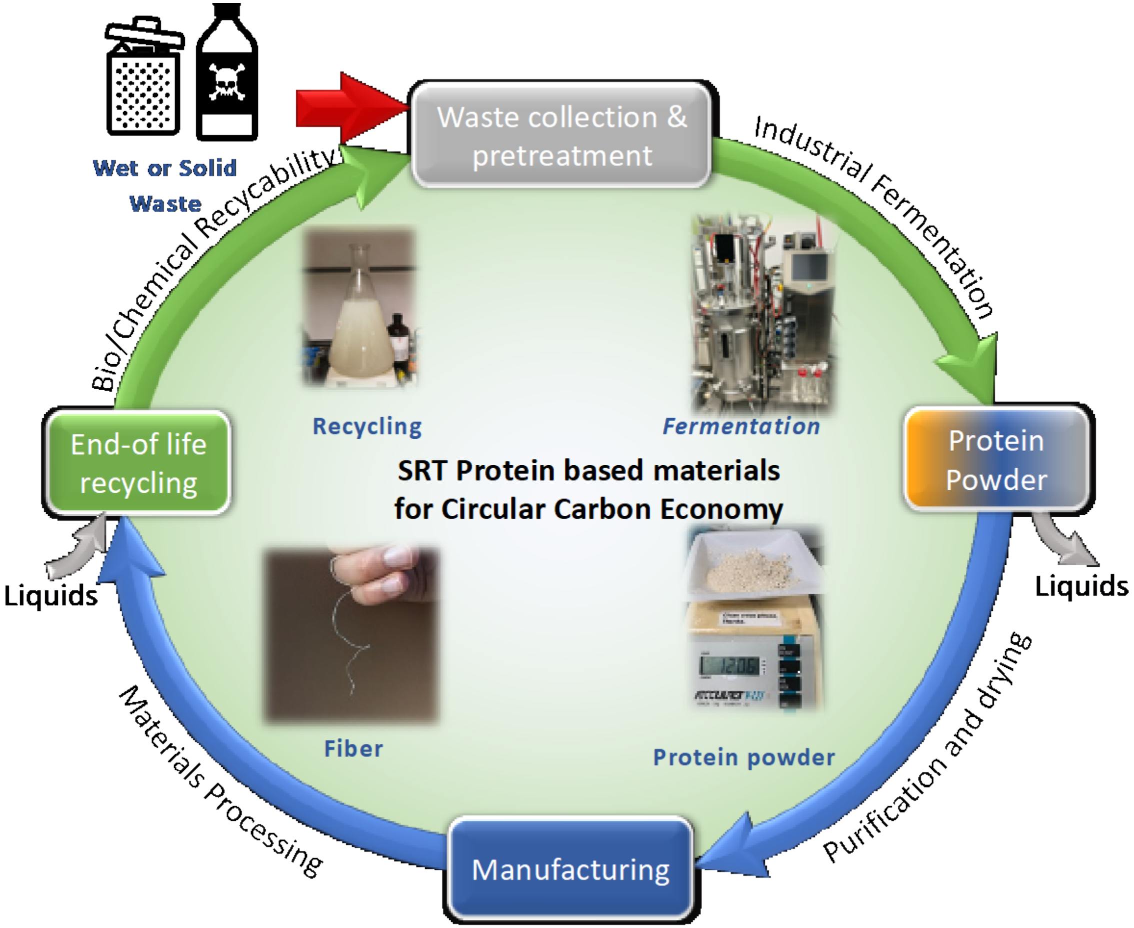
- **Durability**: repeatable performance during multiple cycles

- **Safety**: Non-toxic, non-flammable, non-explosive, non-reactive, non-corrosive

Bio-based materials derived from squid ring teeth proteins



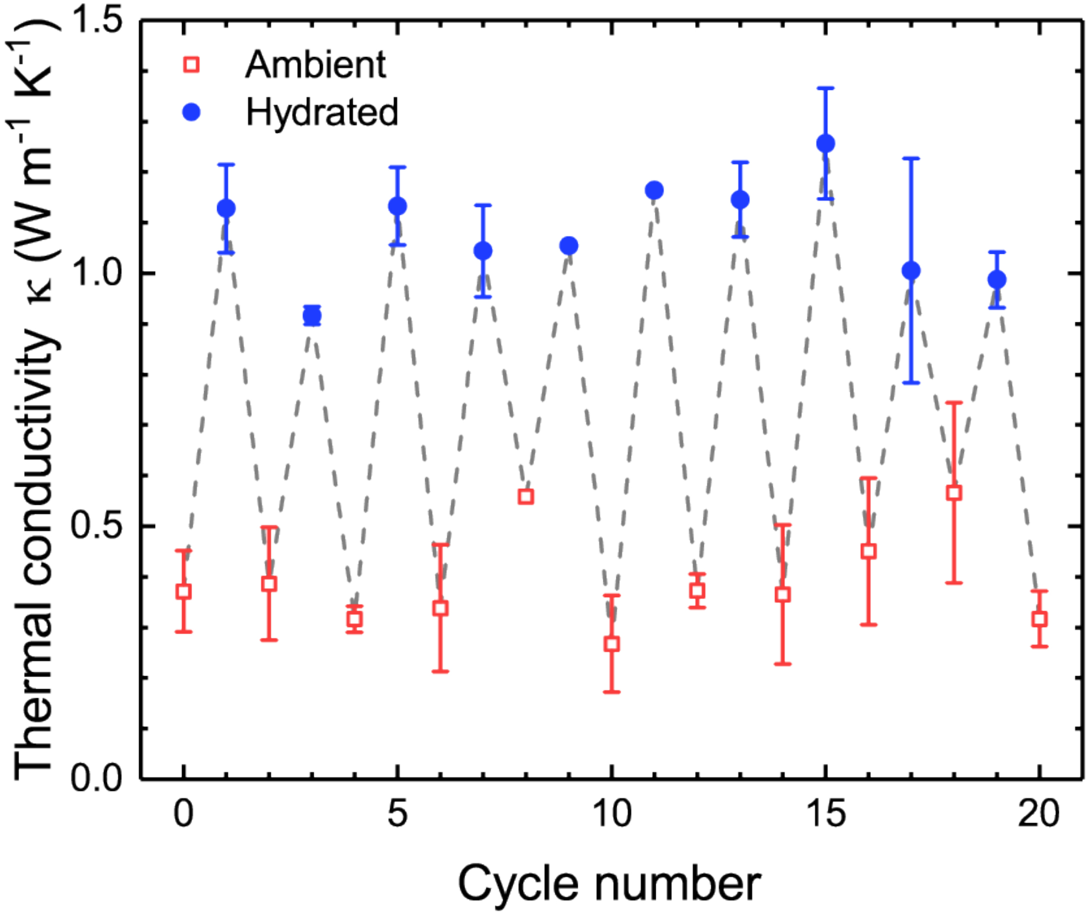




PNAS **113**, 6478 (2016)

Advanced Functional Materials **24**, 7401 (2014)

SRT proteins: unprecedented thermal conductivity switching

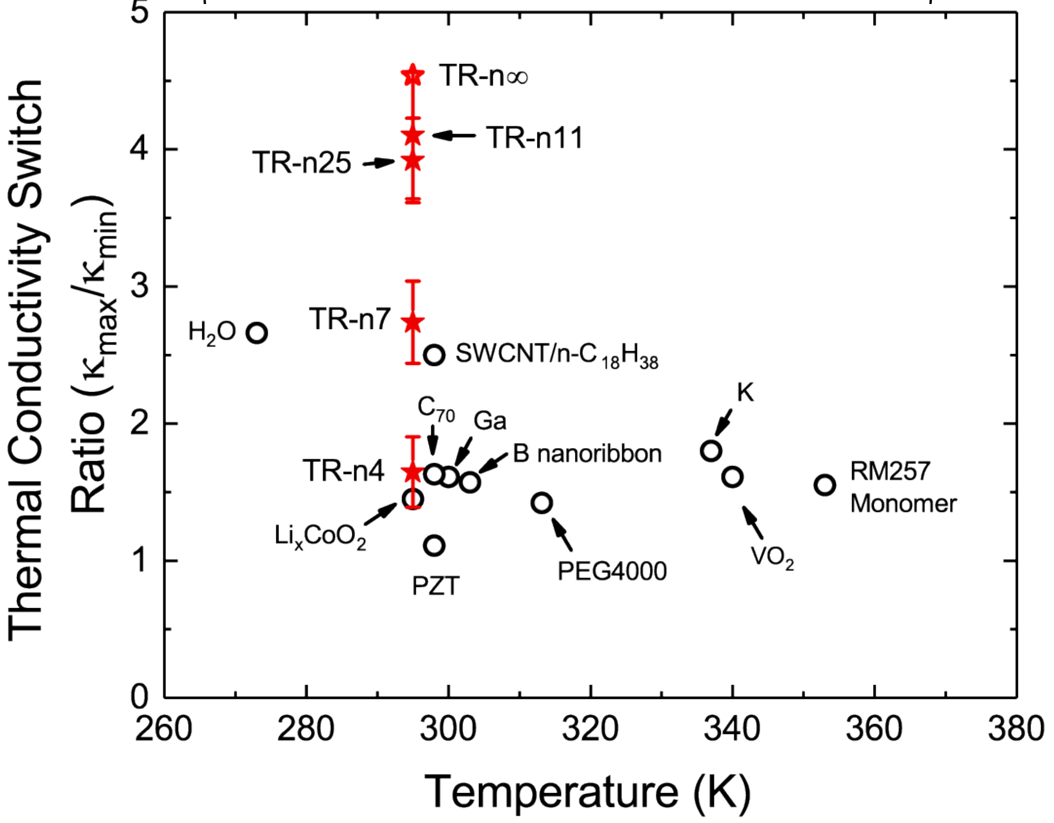


Squid-inspired tandem repeat (TR) proteins

STGTLSYGYGGLYGGLYGGLGYGPAAASVSTVHHP

Amorphous (disordered)

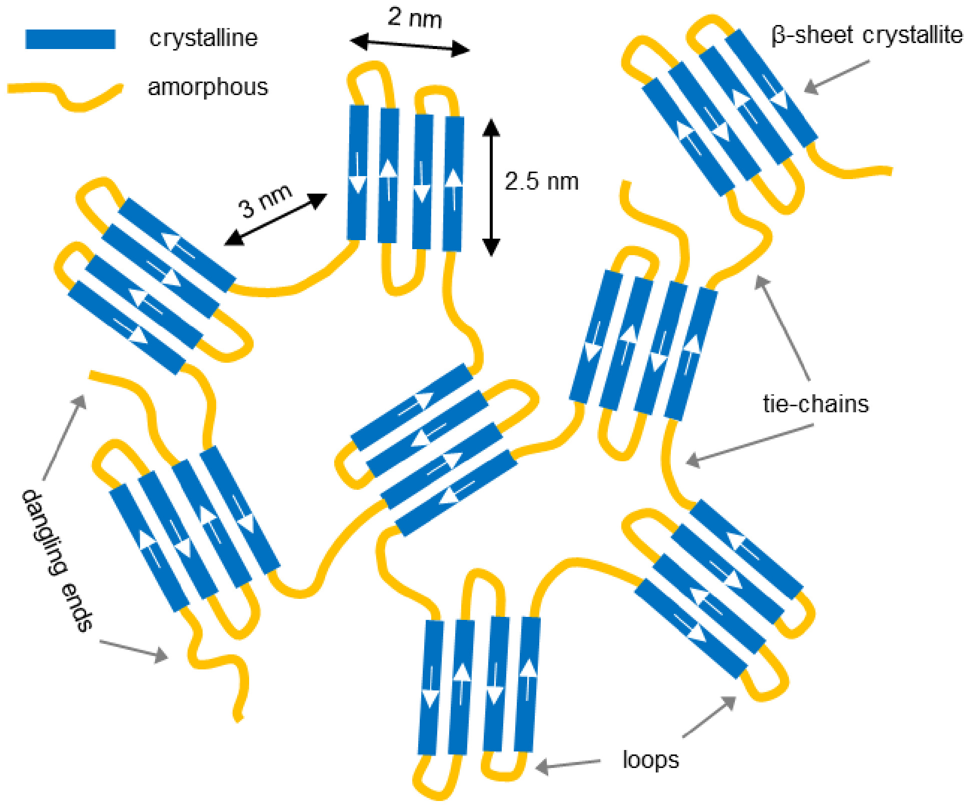
Crystalline (β-sheet)

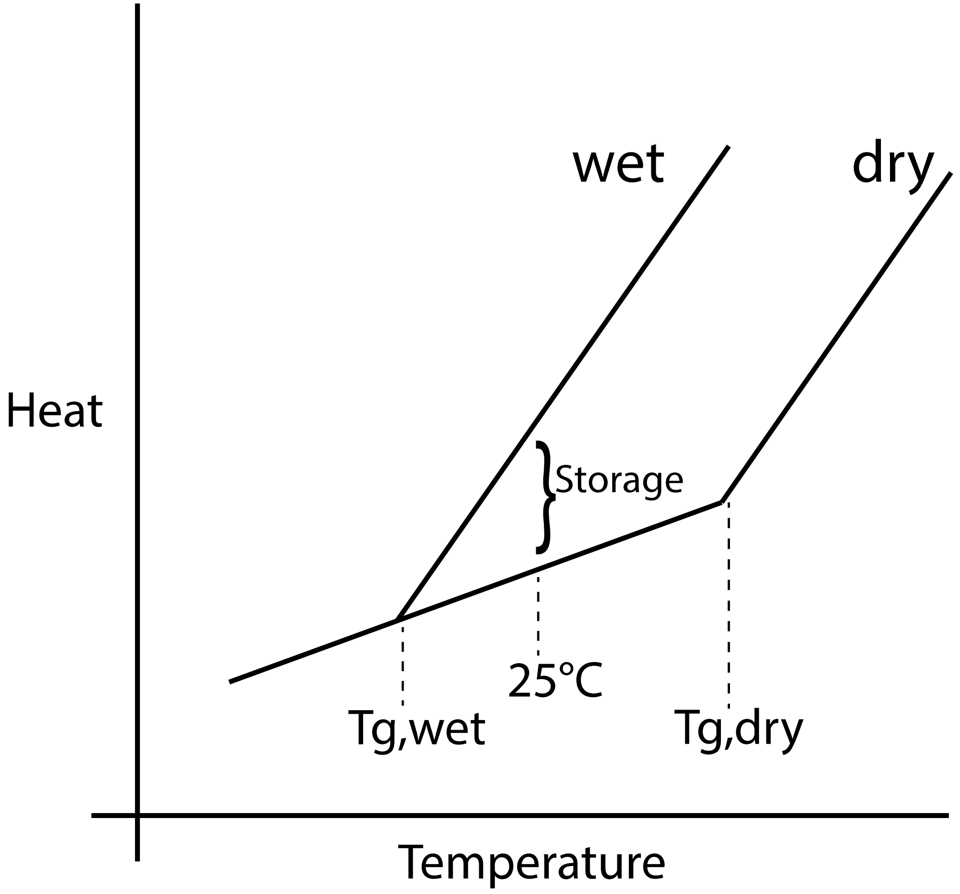


Tomko *et al. Nature Nanotechnology* **13**, 959 (2018)

SRT proteins: a novel approach to energy storage

Plasticizing squid ring teeth (SRT) for on-demand, room temperature energy storage: modulating the glass transition temperature





Tomko *et al. Nature Nanotechnology* **13**, 959 (2018)

Bio-based materials derived from squid ring teeth proteins

- **Thermal properties**: high energy storage density (> 100 kWh/m^3), switchable thermal conductivity at low T (>5X)
  - **Challenge**: design proteins with increased switching and energy density
- **Manufacturing properties**: scalable to < $15/kWhr at scale
  - **Challenge**: Create bio-based protein PCM at scale with similar performance/purity as lab-scale research results
- **Durability**: repeatable performance during multiple cycles
  - **Advantage**: Self-healing ability of SRT offers unique solution
- **Safety**: Non-toxic, non-flammable, non-explosive, non-reactive, non-corrosive
  - **Advantage**: All of the above and carbon circular manufacturing

Project approach

TANDEM REPEAT

PCM manufacturing

Georgia Tech

Thermal property validation (round robin), system modeling

UNIVERSITY of VIRGINIA

SCHOOL of ENGINEERING & APPLIED SCIENCE

Thermal property testing, cycling

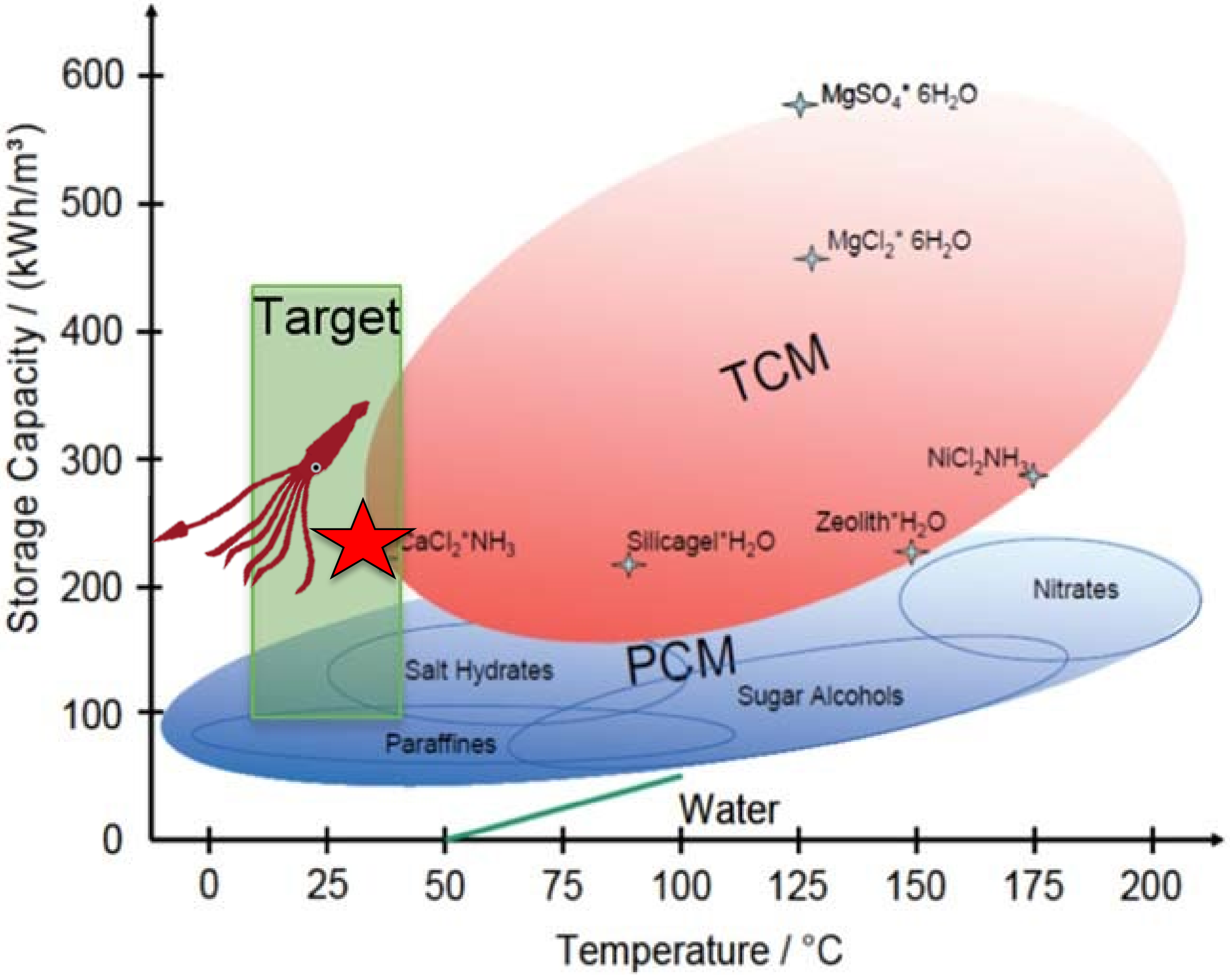
Output to DoE

U.S. DEPARTMENT OF ENERGY

Energy Efficiency & Renewable Energy

Impact

- A new PCM for energy storage with new start of the art thermal properties
- Bio-based PCM manufactured with carbon *circular* process with competitive $/kWh at scale
- Redefining energy storage design in buildings with *self-healing* PCM, increasing lifetime in addition to energy efficiency



Impact – Alignment with Energy Storage Grand Challenge 2030

Vision: By 2030, the U.S. will be the world leader in energy storage utilization and exports, with a secure domestic manufacturing supply chain independent of foreign sources of critical materials.

- **Technology development:** enhancing diversity of storage opportunities and enabling technologies; strengthening R&D ecosystem
- **Technology transfer:** Accelerating tech-to-market (Tandem Repeat)
- **Policy and valuation:** Developing models from material-to-system performance of SRT energy storage devices including technoeconomics
- **Manufacturing and supply chain:** Developing novel and scalable routes for protein fermentation and manufacturing for genetic engineering of bio-based PCMs
- **Workforce:** Training in both university and private sectors

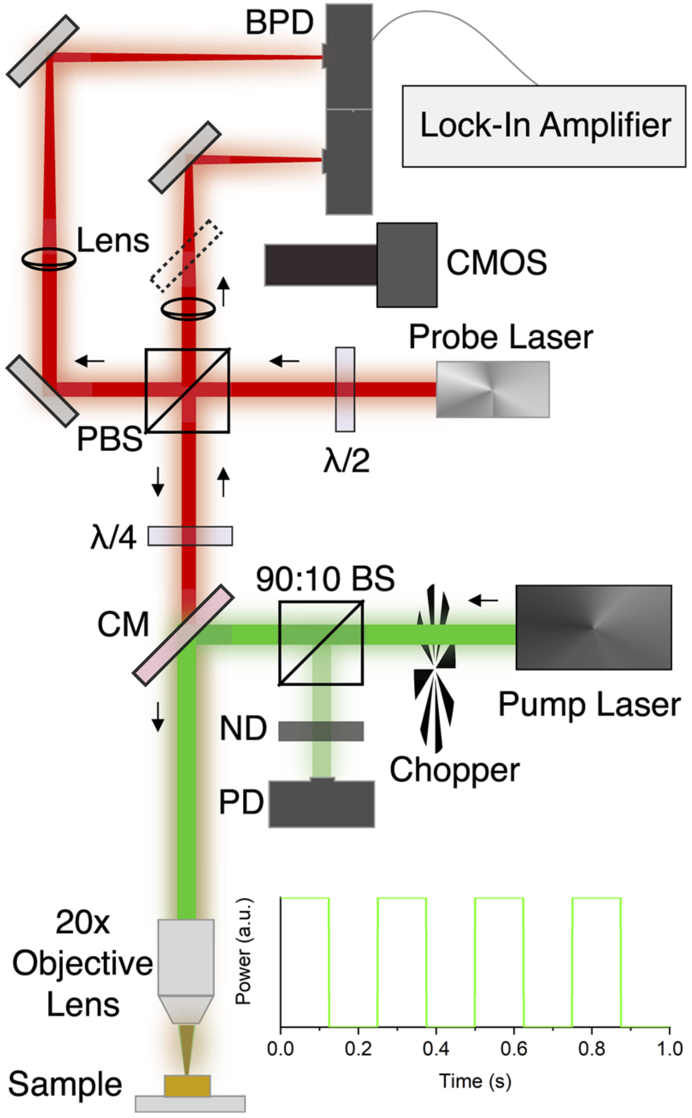
Progress

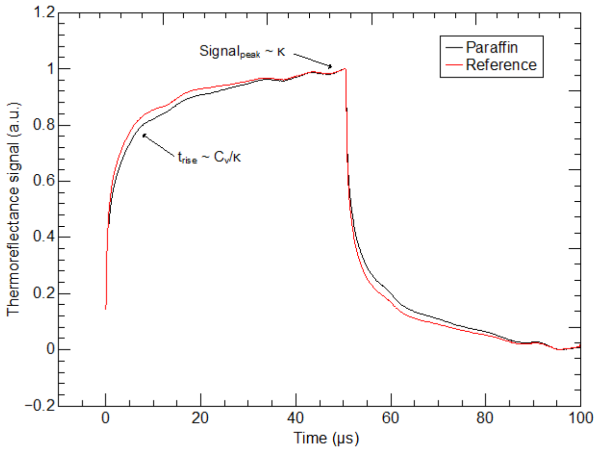
- High risk/high reward project due to challenges in manufacturing and thermal performance of novel bio-based PCM
- Early stage project, and focused on "feasibility" study of manufactured/scaled PCM hitting metrics (see below)
- Identified and designed system to achieve system cost of $15/kWh at the 250,000 L scale utilizing SRT PCM.

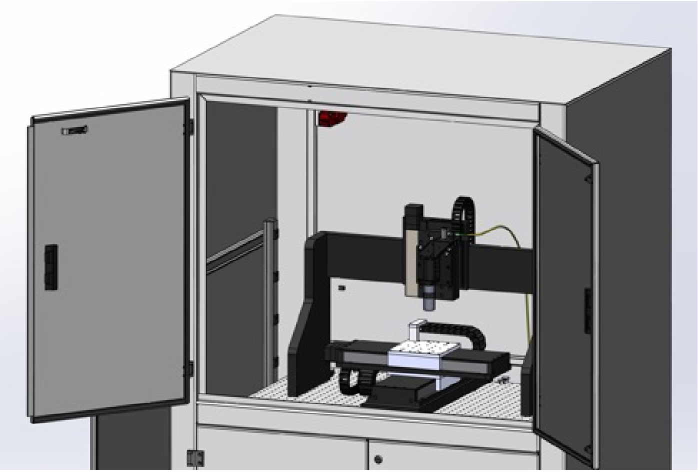
Related Task	Y1 Go/No-Go Milestones	Status at end of Q4
1.2	Synthesize 0.5 kg of SRT-based PCM at >80% purity and with a yield of >1 g/L	Complete
1.3.1	Achieve thermal conductivities >1 W m^{-1} K^{-1}, switching ratios >4x	Complete
1.3.2	Demonstrate energy storage densities > 30 kWhr m^{-3}	Complete
1.3.1 & 1.3.2	Cycling durability of >75% over 100 cycles.	Complete

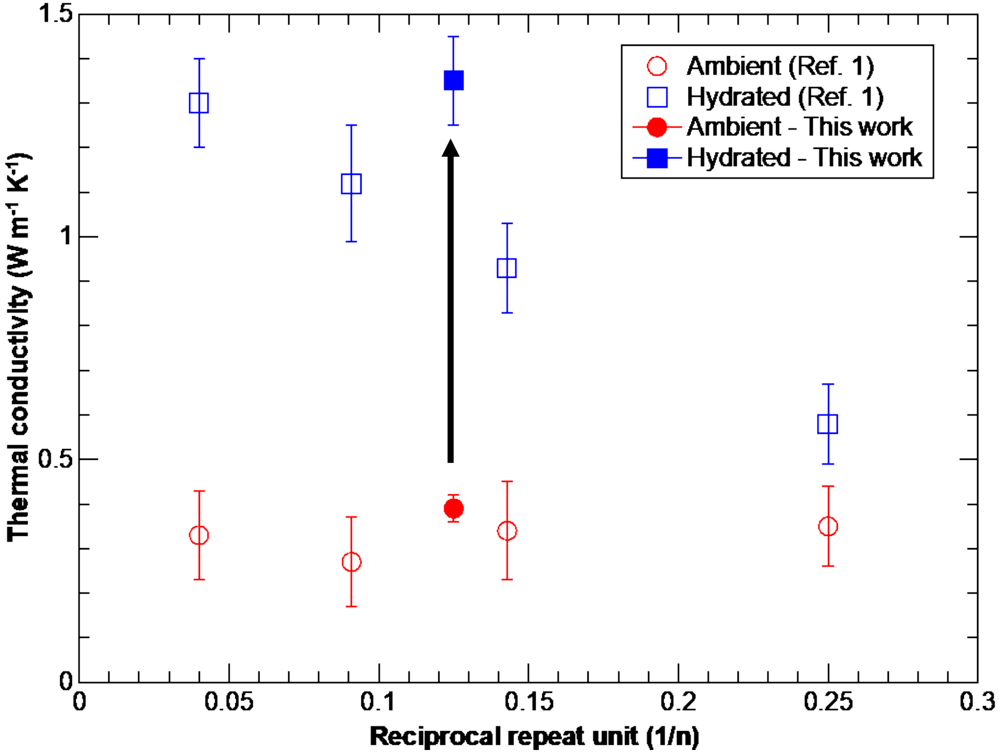
Progress – Thermometry development for PCMs – SSTR

Steady-state thermoreflectance as **high-throughput** measures of *k* and *C* during PCM phase change for thin films and bulk









Rev. Sci. Instrum. **90**, 024905

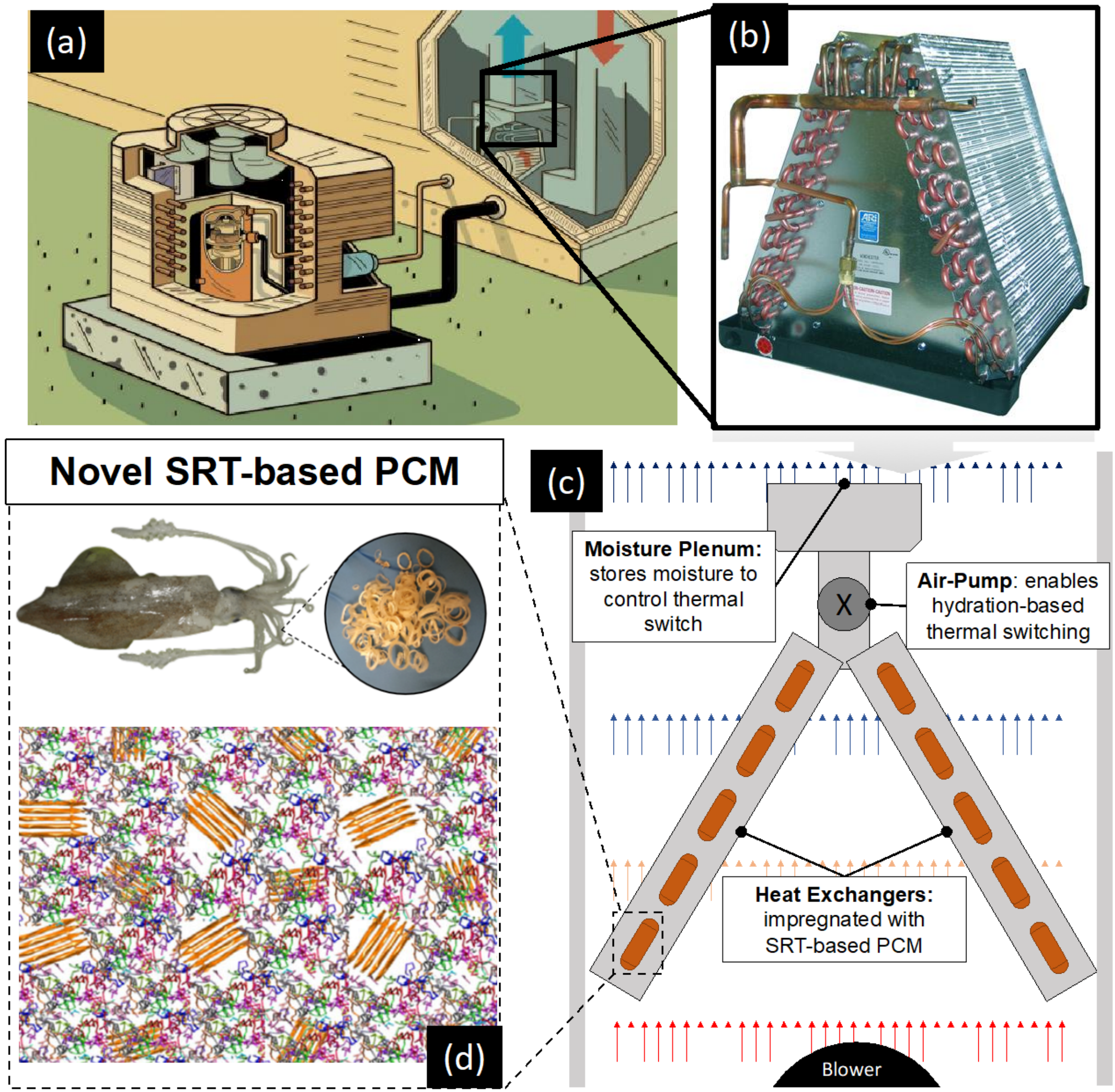
Stakeholder Engagement

- Early-stage project, and focused on “feasibility” study of manufactured/scaled PCM hitting metrics (next slide)
- Partnership with Tandem Repeat enables direct tech transition to small business involved with manufacturing of SRT
- Scale up production at Tandem has involved close collaboration and potential future partnerships with large scale fermentation facilities and companies to accelerate future development and commercial

Potential immediate tasks beyond Y2 EOP
Advanced Manufacturing of a heat exchange prototype unit using thermoplastic SRT optimized in Y2.
Demonstrate building-scale prototype dynamic switchable heat exchanger integrated with air handler in a conventional vapor compression system based on system design and technoeconomic analysis in Y2.

Remaining Project Work – Y2

- Continue feasibility demonstration of this novel bio-based PCM by increasing thermal metrics at higher yields (EOP goals)
  - 8X switchable thermal conductivity
  - Energy storage density > 100 kWhr/m^3
  - > 75% durability over 500 cycles
  - Clear pathway to scaling (1 kg demonstrate with plan for > 10 kg, 5 g/L) and building integration with techno-economic and psychrometric analysis



Thank You

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REFERENCE SLIDES

Project Budget

Project Budget:

Budget History					
4/1/2020 – FY 2020 (past)		FY 2021 (current) 10/1/2020-9/31/2021		FY 2022 – 6/30/2022 (planned)	
DOE	Cost-share	DOO	Cost-share	DOE	Cost-share
$219,939	$42,337	$743,282	$190,716	$786,779	$225,280

Variances: Due to Covid issues preventing us from being able to track with our originally proposed spend plan in Y1 (note, program started 4/1/2020), our Y1 Cost Share was not fully expensed until 5/2021.

Cost to Date: DOE: $963,221.25; Cost Share: $233,053

Additional Funding: None

Project Plan and Schedule: Y1 (complete)

Task	Go/No-Go Milestones	Status at end of Q4	Projected status at end of Budget Period 1 and notes
1.2	Synthesize 0.5 kg of SRT-based PCM at >80% purity and with a yield of >1 g/L	Complete	Complete
1.3.1	Achieve thermal conductivities >1 W m^{-1} K^{-1}, switching ratios >4x	Complete	Complete
1.3.2	Demonstrate energy storage densities of energy storage densities > 30 kWhr m^{-3}	Complete	Complete
1.3.1 and 1.3.2	Thermal conductivity and energy storage durability of >75% over 100 cycles.	Complete	Complete

Project Plan and Schedule: Y2 (current)

End of Project Goals

- 8X switchable thermal conductivity
- Energy storage density > 100 $kWhr/m^3$
- > 75% durability over 500 cycles
- Clear pathway to scaling (1 kg demonstrate with plan for > 10 kg, 5 g/L) and building integration with techno-economic and psychrometric analysis

Project Plan and Schedule: Future beyond 2 year award

Potential future Tasks
Advanced Manufacturing of a heat exchange prototype unit using thermoplastic SRT optimized in Y2.
Demonstrate building-scale prototype dynamic switchable heat exchanger integrated with air handler in a conventional vapor compression system based on system design and technoeconomic analysis in Y2.