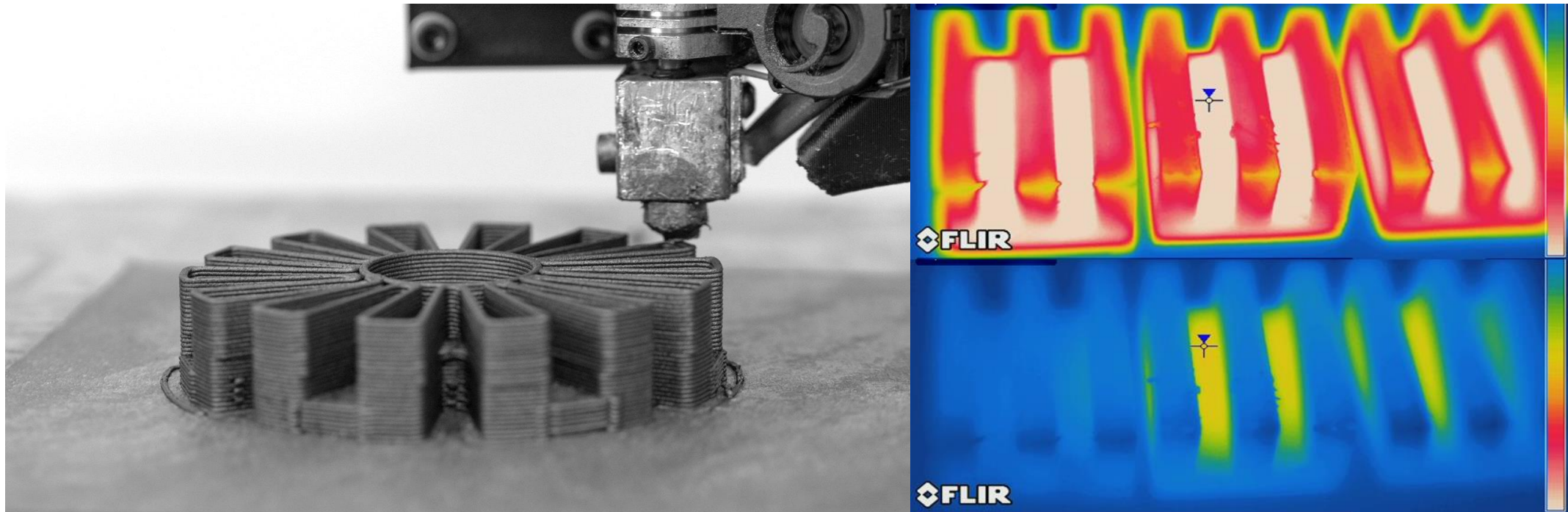


Additive Manufacturing to Enable High Performance Thermal Energy Storage Products



TCPoly, Inc.; National Renewable Energy Laboratory; Embry Riddle Aeronautical University

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STTR Phase II Award No. DE-SC0020764

Project Summary

Objective and Outcome

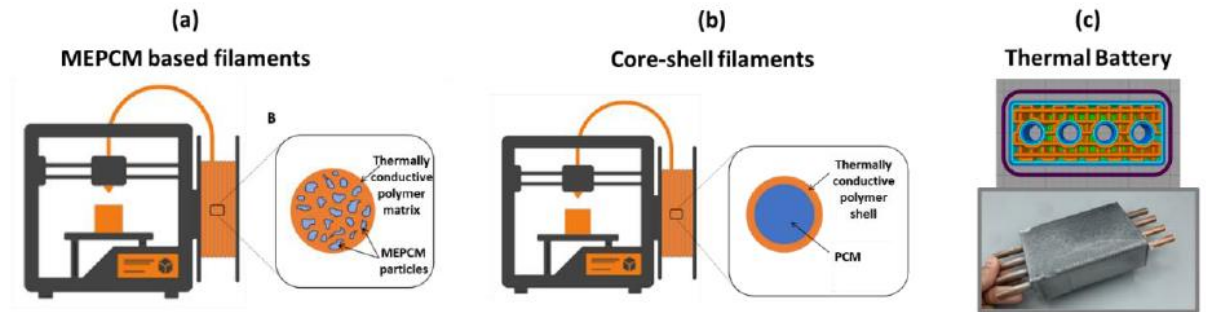
This project will advance the use of TES in buildings and other end uses by enabling 3D printing of high-performance PCM devices.

Three different techniques to 3D print PCM products are being explored for commercialization.

Development of 3D-printable PCMs will enable rapid prototyping of innovative designs and form factors and enable manufacturing of final parts with reduced time and material cost.

Team and Partners

- TCPoly, Inc.
- NREL
- Embry Riddle Aeronautical University



(a) Micro-encapsulated PCM (MEPCM)-based filaments for 3D printing, (b) Core-shell PCM/thermally conductive composite filament for 3D printing, (c) PCM back-filled 3D-printed structures.

Stats

Performance Period: Aug 2021–Aug 2023

DOE Budget: \$1,098k, Cost Share: \$0k

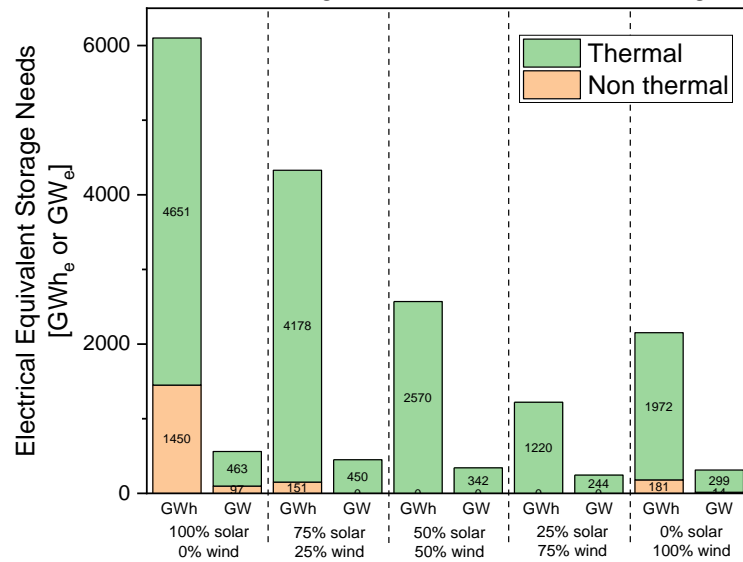
Milestone 1: 3D-printable MEPCM filament w/ $\Delta H > 60$ J/g

Milestone 2: Core-shell filament w/ $>50\%$ core volume

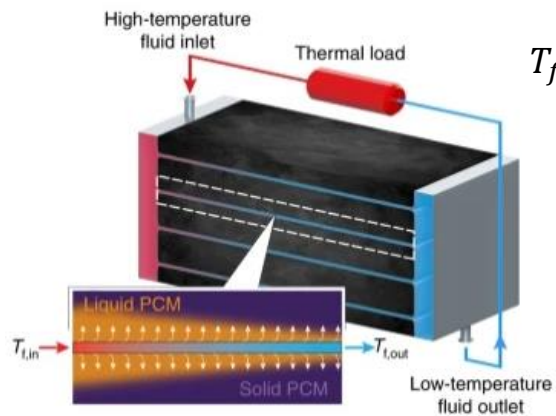
Milestone 3: Demonstrate 3D-printed heat exchanger w/ developed filaments

Problem

2050 Storage Needs with ASHP Heating



- Thermal energy storage (TES) in buildings can contribute to decarbonization by reducing energy consumption, increasing flexibility, and promoting the use of renewable sources.
- However, technical barriers must be overcome before widespread adoption is feasible.
- This project—3D printing high-performance phase change materials (PCM)—advances the viability and commercialization of building TES by enabling rapid prototyping, and reducing time and material cost for manufacturing.



$$T_{f,out} \approx 2 \left[\bar{T}_t + \underbrace{\dot{q} (R_{PCM} + R_f + R_{contact})}_{\text{thermal resistances}} \right] - T_{f,in}$$

$$R_{PCM} \approx \frac{L}{kA}$$

$$R_f \approx \frac{1}{hA}$$

Sources:

[1] A Odukumaiya et al., *Energy & Environmental Science* 14 (10), 5315 (2021).

[2] J Woods et al., *Nature Energy* 6 (3), 295 (2021).

Alignment and Impact



Support rapid decarbonization of the U.S. building stock in line with economywide net-zero emissions by 2050 while centering equity and benefits to communities



Increase building energy efficiency

Reduce onsite energy use intensity in buildings 30% by 2035 and 45% by 2050, compared to 2005



Accelerate building electrification

Reduce onsite fossil-based CO₂ emissions in buildings 25% by 2035 and 75% by 2050, compared to 2005



Transform the grid edge at buildings

Increase building demand flexibility potential 3X by 2050, compared to 2020, to enable a net-zero grid, reduce grid edge infrastructure costs, and improve resilience.



Prioritize equity, affordability, and resilience

Ensure that 40% of the benefits of federal building decarbonization investments flow to disadvantaged communities



Reduce the cost of decarbonizing key building segments 50% by 2035 while also reducing consumer energy burdens



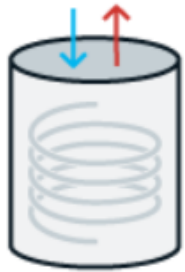
Increase the ability of communities to withstand stress from climate change, extreme weather, and grid disruptions

Impact of additive manufacturing for PCM TES:

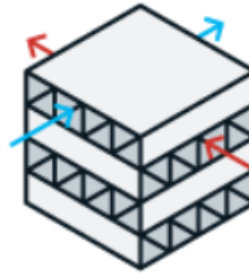
- Lower upfront cost for manufacturing equipment.
- Rapid prototyping of innovative designs.
- Manufacturing of net shape parts with reduced time and material cost.
- Heat transfer efficient geometries that are unattainable with traditional manufacturing.
- Applications in other verticals beyond buildings:
 - Electronics, pharmaceuticals, cold chain, wearables, etc.

Approach

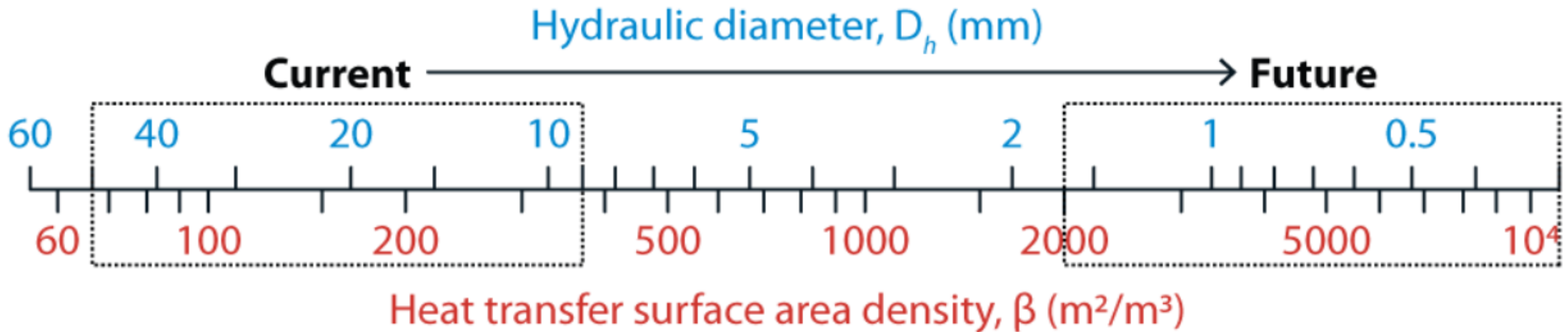
Vision for the future of TES heat exchangers with respect to magnitude of length scales and surface-area-to-volume ratios



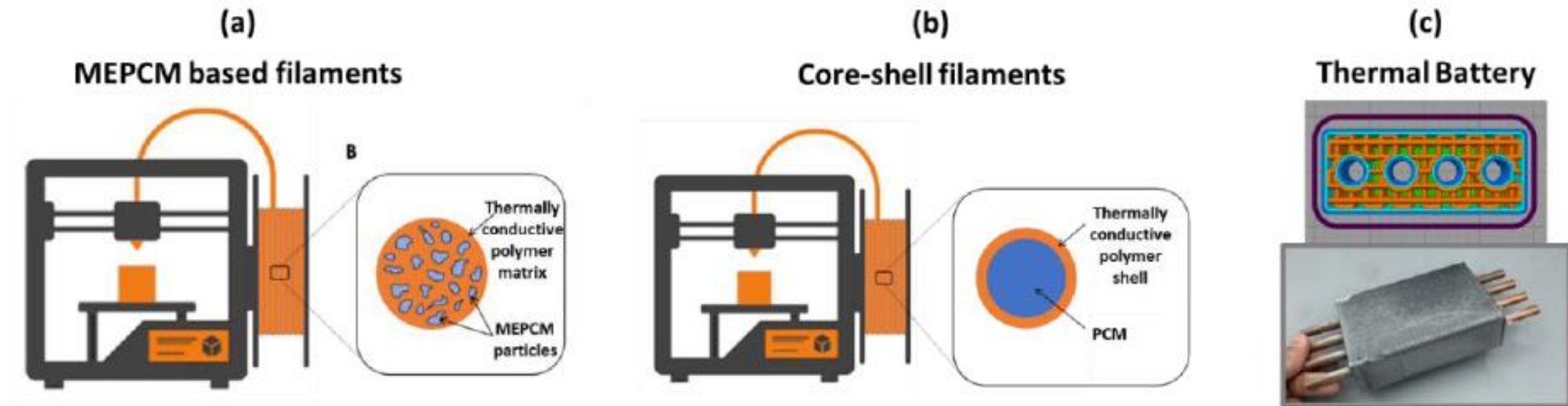
Large TES Tanks
(10-40 mm)



Compact Modular Composite TES
(1-3 mm)



Outcomes: 3 Approaches to AM PCM TES Devices

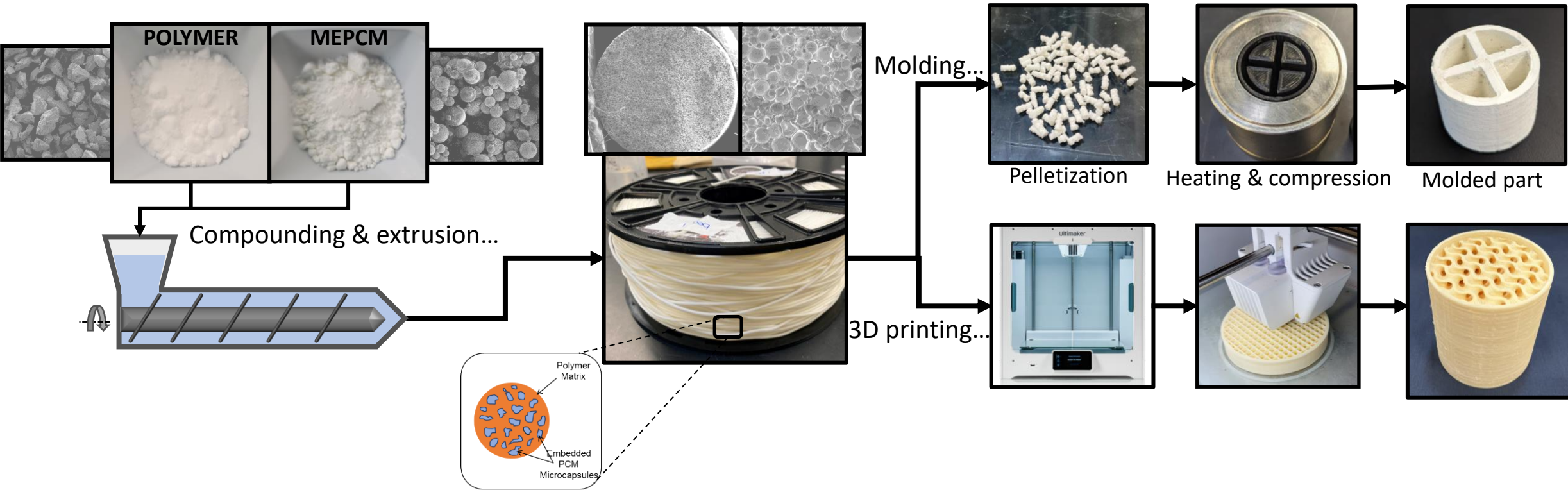


(a) Micro-encapsulated PCM (MEPCM)-based filaments for 3D printing.

(b) Core-shell PCM/thermally conductive composite filament for 3D printing.

(c) PCM back-filled 3D-printed structures—thermal battery.

Approach: MEPCM Filament



Progress: MEPCM Filament

Characterization of increasing MEPCM ratios

40 wt.%



50 wt.%

60 wt.%

- Smooth surface quality.
- Consistent diameter.
- Flexible.
- Durable while spooling.

70 wt.%



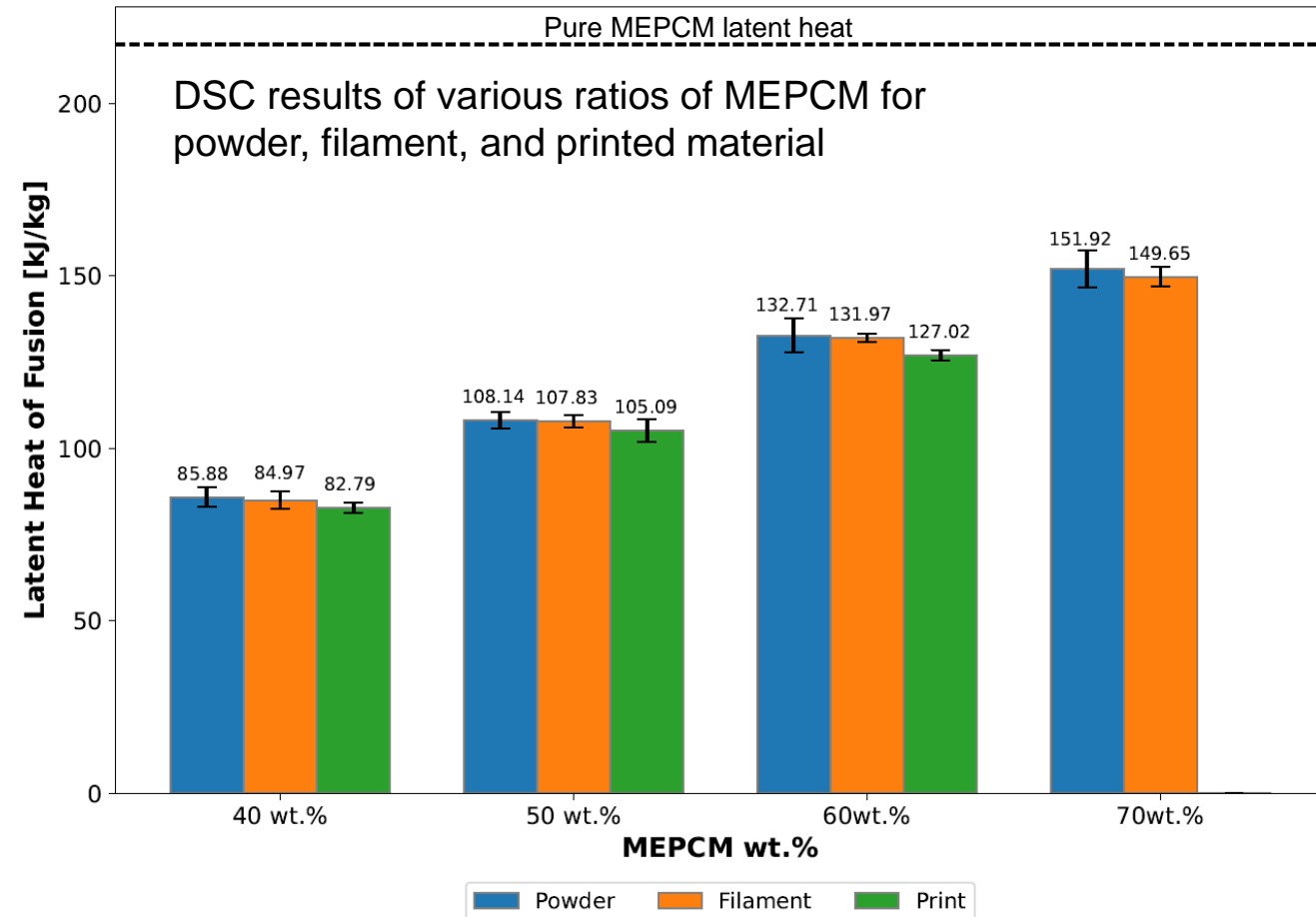
- Rough surface quality.
- Brittle.
- Breaking during spooling.

**Target packing value
between 60 wt% & 70 wt%**

Progress: MEPCM Filament

Characterization of increasing MEPCM ratios

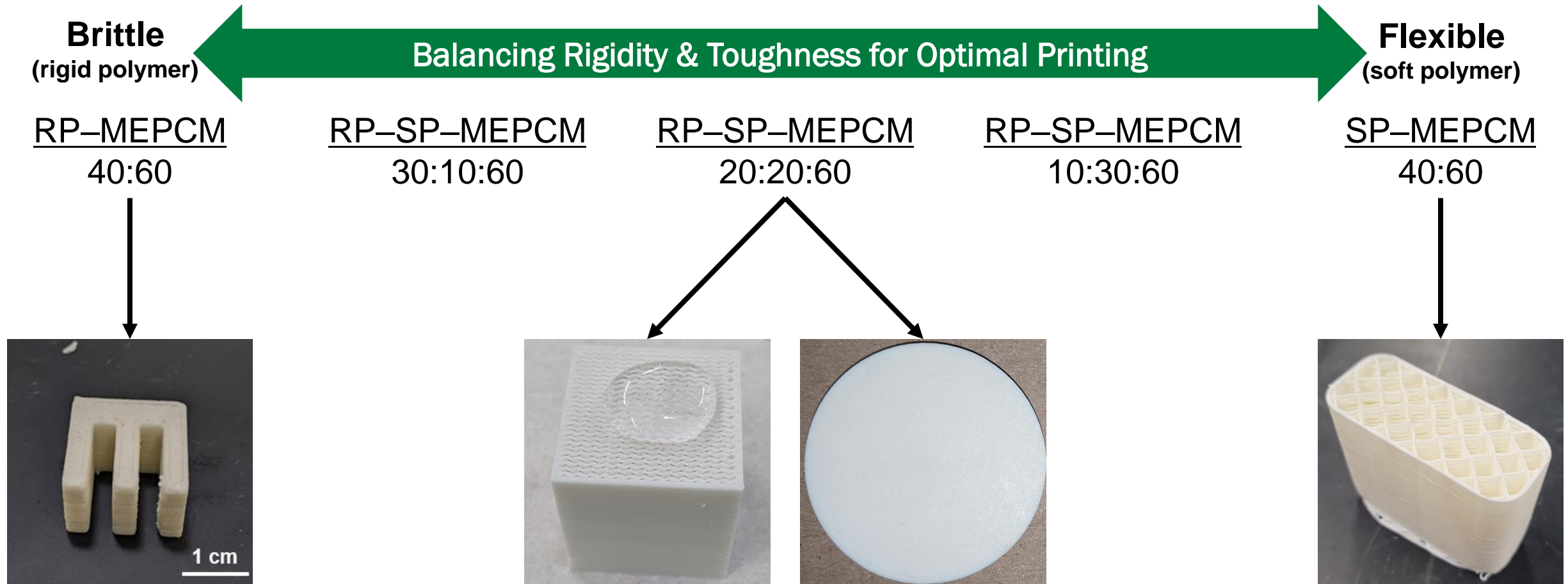
Sample	T_{onset} (°C)	h_{sl} [kJ/kg]	Theo. wt. %
MEPCM Powder	39.83 ± 0.77	217.10 ± 2.89	-
Powders			
40 wt.% MEPCM	40.39 ± 0.46	85.88 ± 2.86	39.6 %
50 wt.% MEPCM	39.82 ± 0.29	108.14 ± 2.30	49.8 %
60 wt.% MEPCM	39.48 ± 0.23	132.71 ± 5.00	61.1 %
70 wt.% MEPCM	39.52 ± 0.10	151.92 ± 4.89	69.9 %
Filaments			
40 wt.% MEPCM	39.24 ± 0.11	84.91 ± 2.55	39.1 %
50 wt.% MEPCM	38.90 ± 0.10	107.83 ± 1.69	49.6 %
60 wt.% MEPCM	38.84 ± 0.06	131.97 ± 0.13	60.8 %
70 wt.% MEPCM	39.82 ± 0.62	149.65 ± 2.89	68.9 %
Printed			
40 wt.% MEPCM	39.85 ± 0.72	82.79 ± 1.41	38.1 %
50 wt.% MEPCM	39.60 ± 0.12	105.09 ± 3.34	48.4 %
60 wt.% MEPCM	39.21 ± 0.18	127.02 ± 1.51	58.8 %
70 wt.% MEPCM	-	-	-



Above results are for 43 °C PCM. We have achieved similar results for 6 °C and 24 °C PCMs also.

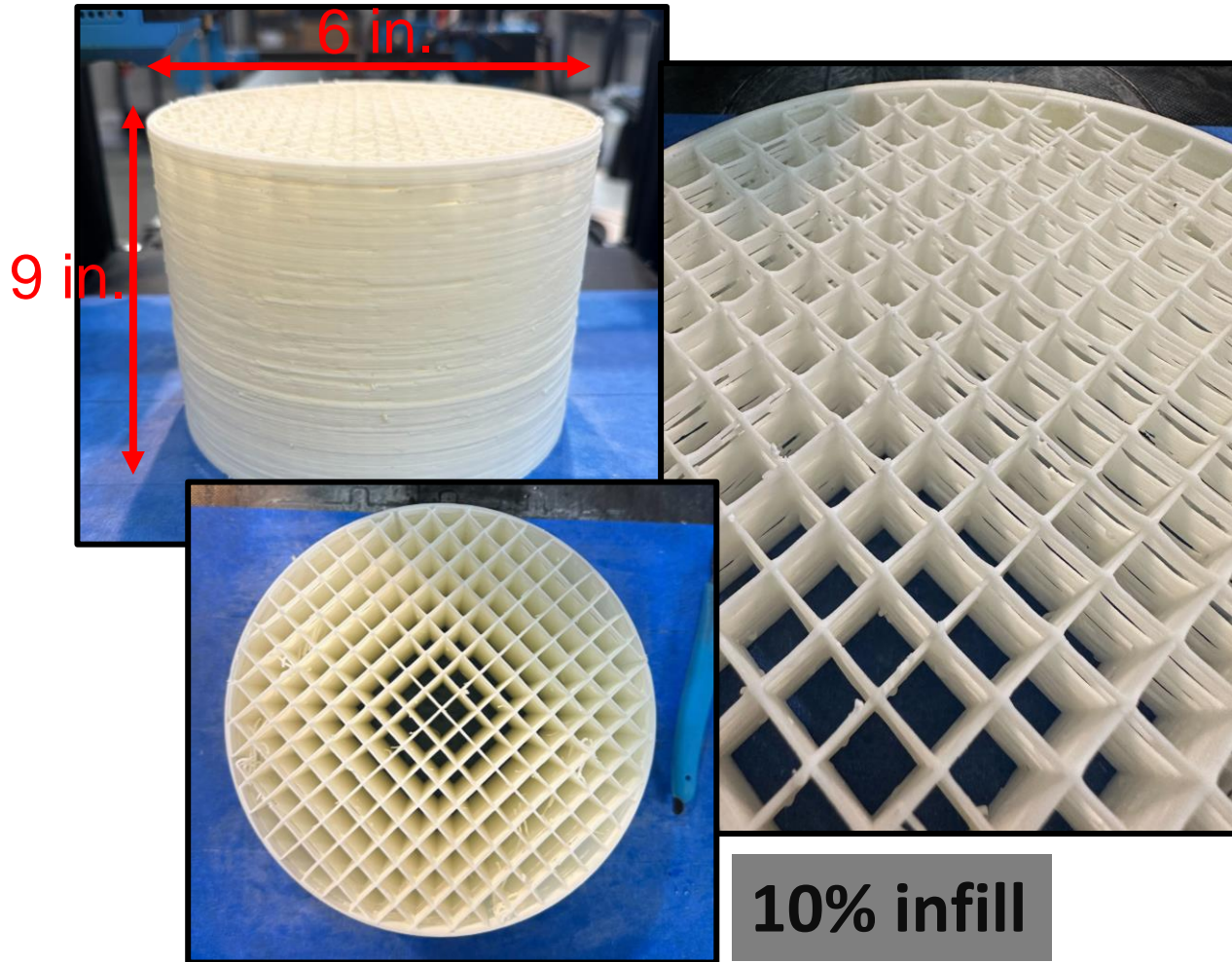
Progress: MEPCM Filament

Tailoring Filament Properties With:



Formulation range can be printed, but extremes currently require highly specific conditions.

Progress: MEPCM Filament



Scaffold Core

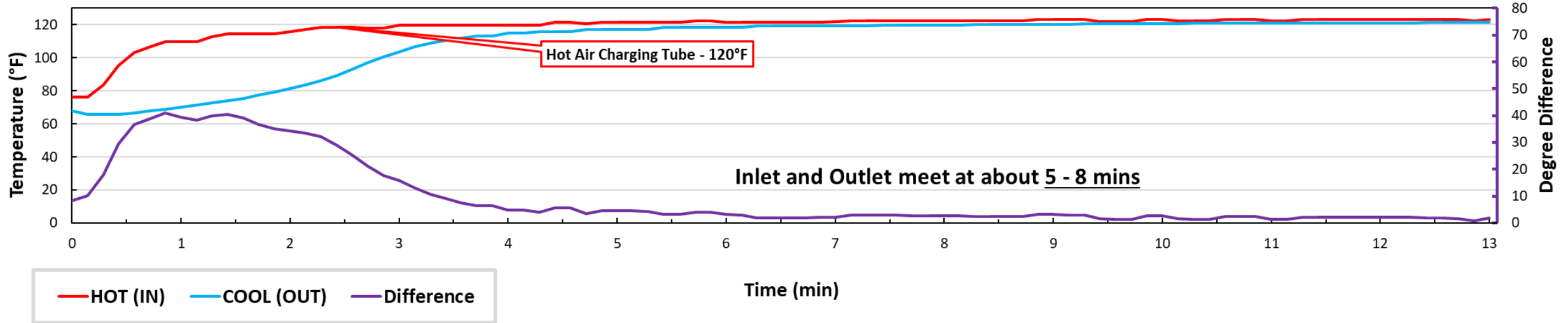
2x, 6 in. x 18 in. total, ~34 Wh thermal capacity



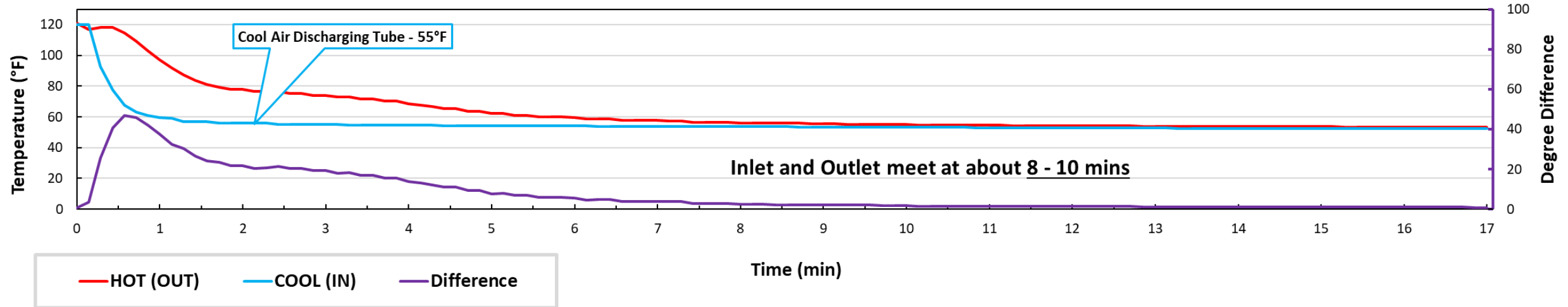
Insulated Test Set Up

Progress: MEPCM Filament

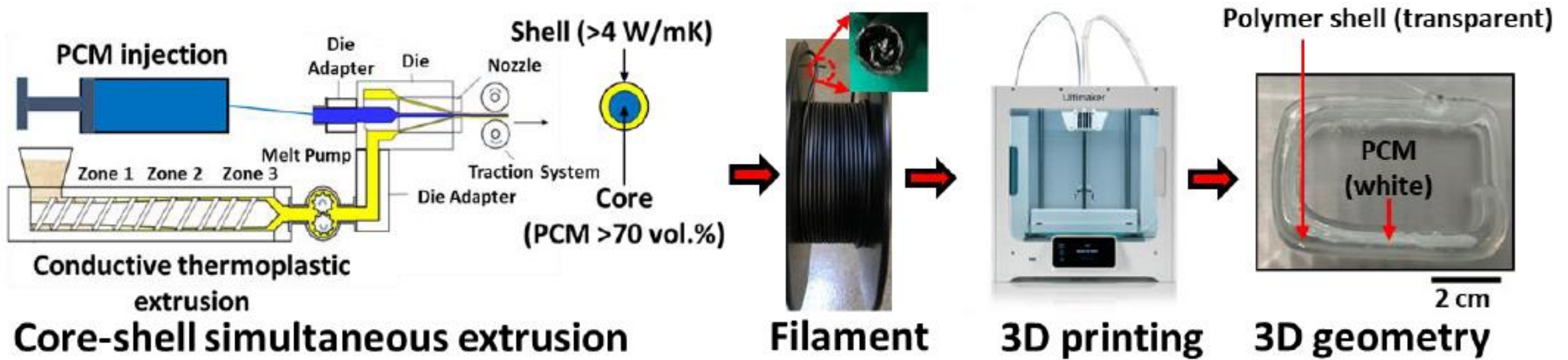
Charging at 81 CFM



Discharging at 81 CFM

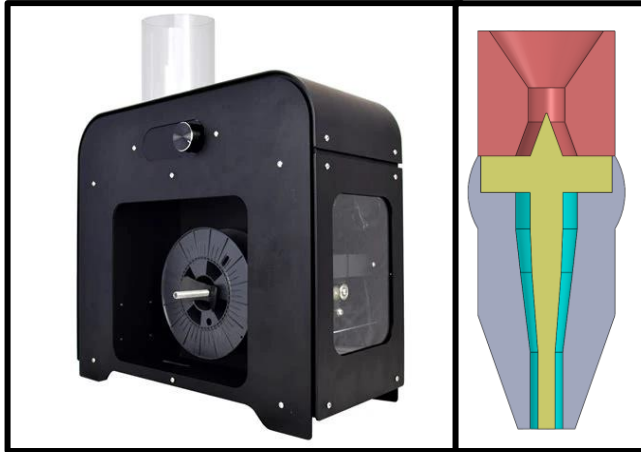


Approach: Core-Shell Filament

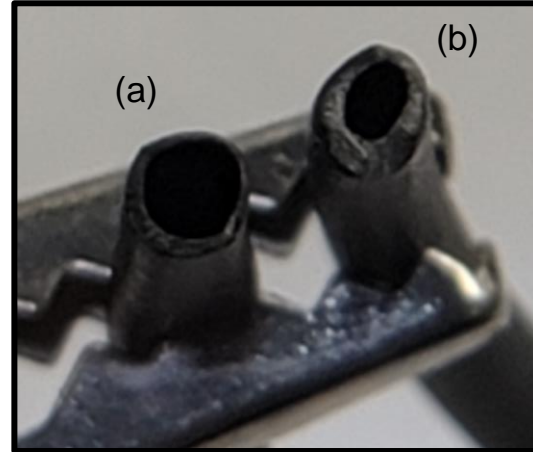


Progress: Core-Shell Filament

Hollow Filament Extrusion



High Thermal Conductivity
Hollow Core Filament

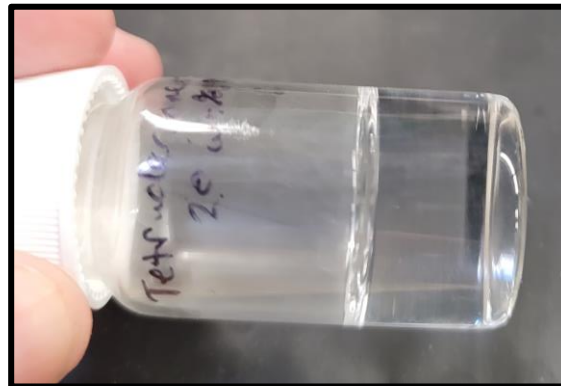


(a) 2.2mm core diameter,
(b) 1.8mm core diameter

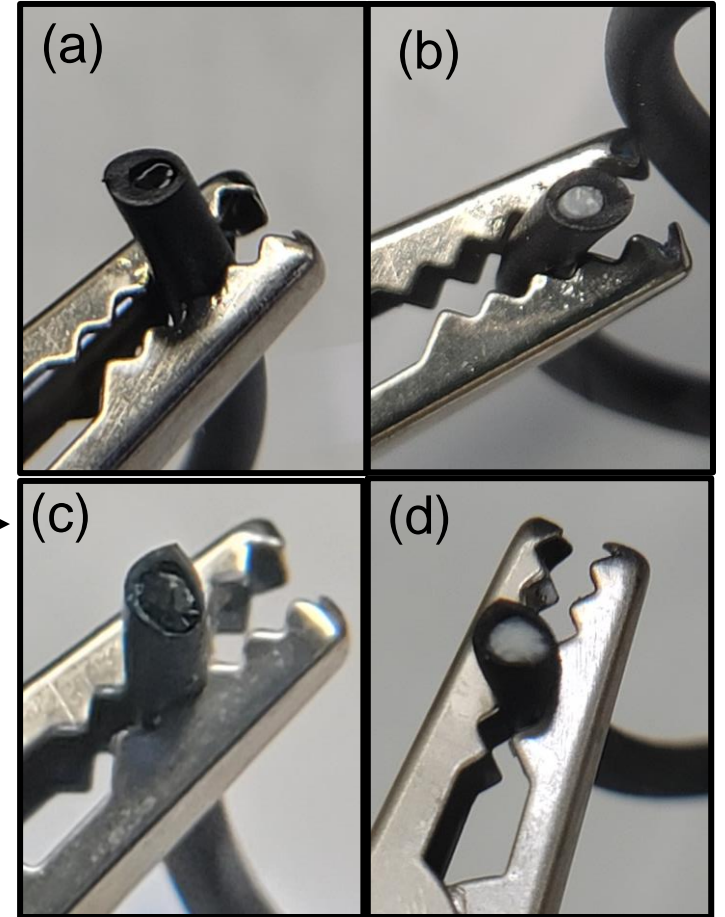
PCM

+

Shape Stabilizer

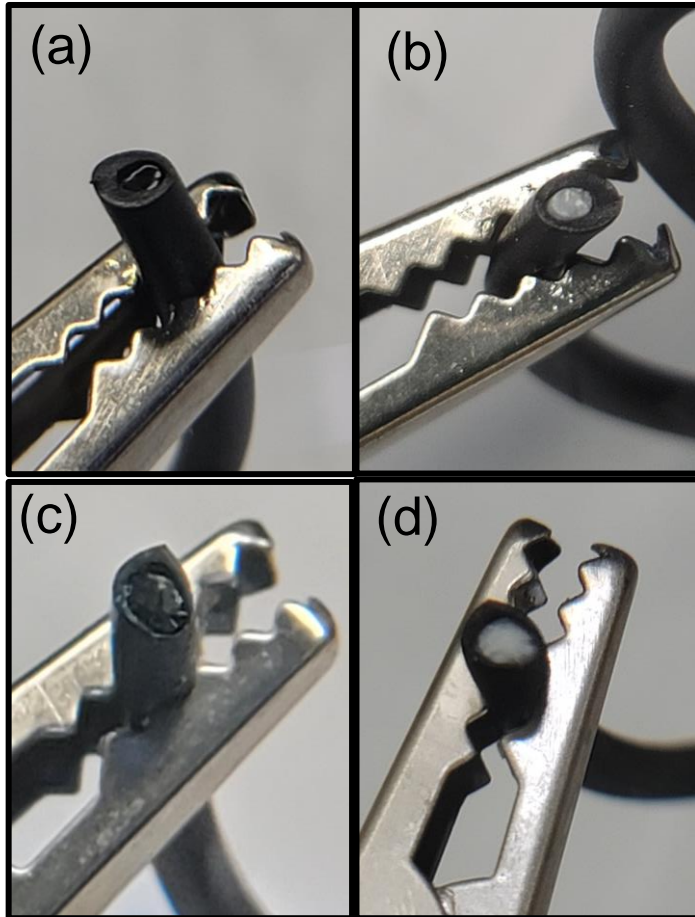


Up to 90wt% PCM Shape Stable



(a) Smaller core melted, (b) smaller core solidified, (c) larger core melted, (d) larger core solidified

Progress: Core-Shell Filament



(a) 1.8mm core melted, (b) 1.8mm core solidified, (c) 2.2mm core melted, (d) 2.2mm core solidified

1.8 mm Core PCM Core wt.%	Onset Tm (°C) ΔHm (J/g)	
50 wt.%	2.8 ± 1.1	19.8 ± 0.9
60 wt.%	2.0 ± 0.1	23.5 ± 0.3
65 wt.%	2.4 ± 0.1	25.9 ± 1.2

2.2 mm Core PCM Core wt.%	Onset Tm (°C) ΔHm (J/g)	
50 wt.%	2.3 ± 0.1	40.3 ± 1.4

Challenges

- Shape stabilization of higher wt.% of PCM backfilled into hollow filament.
- Low latent heat values.
- Challenging to print filament without core and shell separating.

Progress: Outreach

- **Presentations**

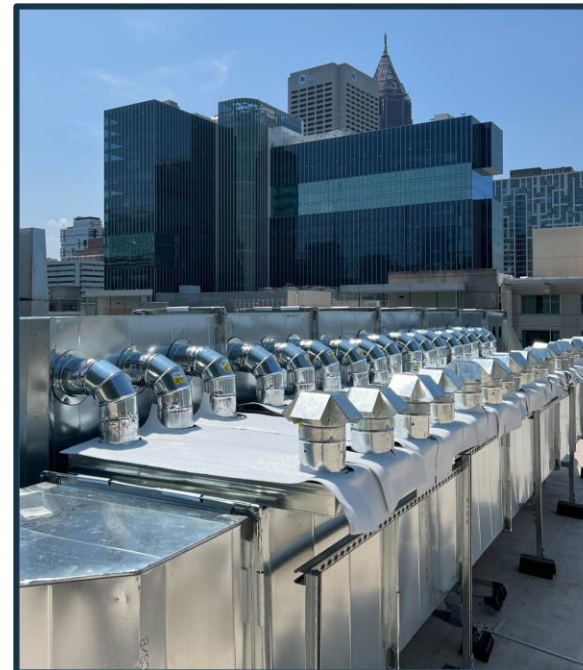
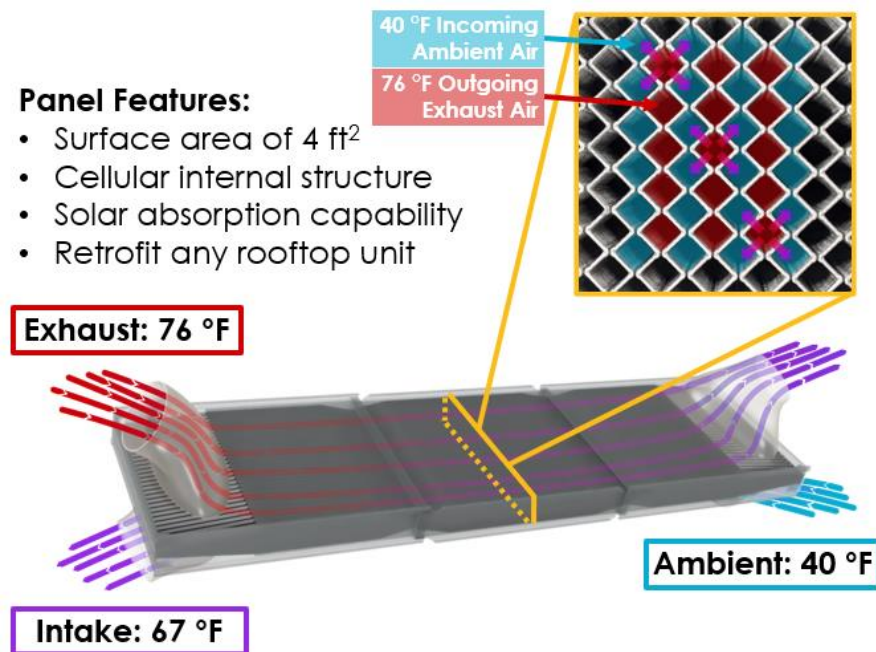
- LBNL Molecular Foundry meeting
- 2023 ASHRAE Winter Conference

- **Publications**

- Singh, P.; Odukamaiya, A.; Smith, M. K.; Aday, A.; Cui, S.; Mahvi, A. Processing of Phase Change Materials by Fused Deposition Modeling: Toward Efficient Thermal Energy Storage Designs. *Journal of Energy Storage* **2022**, 55, 105581. <https://doi.org/10.1016/j.est.2022.105581>.
- Freeman, T.B.; Foster, K.E.O.; Troxler, C.J.; Irvin, C.W.; Aday, A.; Boetcher, S.K.S.; Mahvi, A.; Smith, M.K.; Odukamaiya, A. Advanced Materials and Additive Manufacturing for Phase Change Thermal Energy Storage and Management: A Review. *Advanced Energy Materials* **2023** (accepted)

Future Work

- Phase IIB proposal recently submitted.
- Scale-up and commercialization of MEPCM filament.
- Continued laboratory-scale demonstration of air-side PCM heat exchanger.
- Design integration and field demonstration of PCM heat exchanger in HVAC air loop.



Thank You

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STTR Phase II Award No. DE-SC0020764

REFERENCE SLIDES

Project Execution

Legend: ● Milestones	M1	M3	M5	M7	M9	M11	M13	M15	M17	M19	M21	M23
Task 1: MEPCM filament development	[Shaded]											
1.1: Develop 1.75 mm and 2.85 mm diameter filaments with maximum achievable MEPCM loading in 6 °C, 24 °C, and 43 °C transition temperature	[Shaded]											
1.2: Characterize thermal, mechanical, and morphological properties of developed filaments					●							
1.3: Experimentally determine optimal print parameters on commercially available benchtop FDM printer							●					
Task 2: Core-shell PCM/thermally conductive composite filament development	[Shaded]											
2.1: Continue development of salt-hydrate (Glauber's salt) PCM development	[Shaded]											
2.2: Bio-based PCM composite development	[Shaded]											
2.3: Develop die and extruder setup for simultaneous co-extrusion of PCM core and thermally conductive shell filament												
2.4: Design of experiment (DOE) to determine ideal print parameters for core-shell filament									●			
2.5: Print and characterize sample parts using developed core-shell filament											●	
Task 3: PCM back-filled thermal battery development	[Shaded]											
3.1: Parametric design evaluation of infill pattern and density of printed thermally conductive structure								●				
3.2: Fluid channel integration into thermal battery for minimized contact resistance												
3.3: Thermal characterization of printed thermal batteries												●

- Project does not have any go/no-go decision points
- All milestones are on track

Team

- **NREL**
 - Wale Odukomaiya (PI)
 - Kyle Foster (postdoc)
 - Thomas Freeman (PhD student/grad intern)
 - Irena Lizier-Zmudzinski (SULI intern)
- **TCPoly, Inc.**
 - Matthew Smith (co-PI)
 - Tamera Green (materials engineer)
 - Cameron Irvin (materials engineer)
- **Embry-Riddle Aeronautical University**
 - Sandra Boetcher (professor)
 - Karl Morgan (graduate student)