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Additive manufacturing of thermal energy storage composites with microencapsulated phase change materials supported in a multi-polymer matrix

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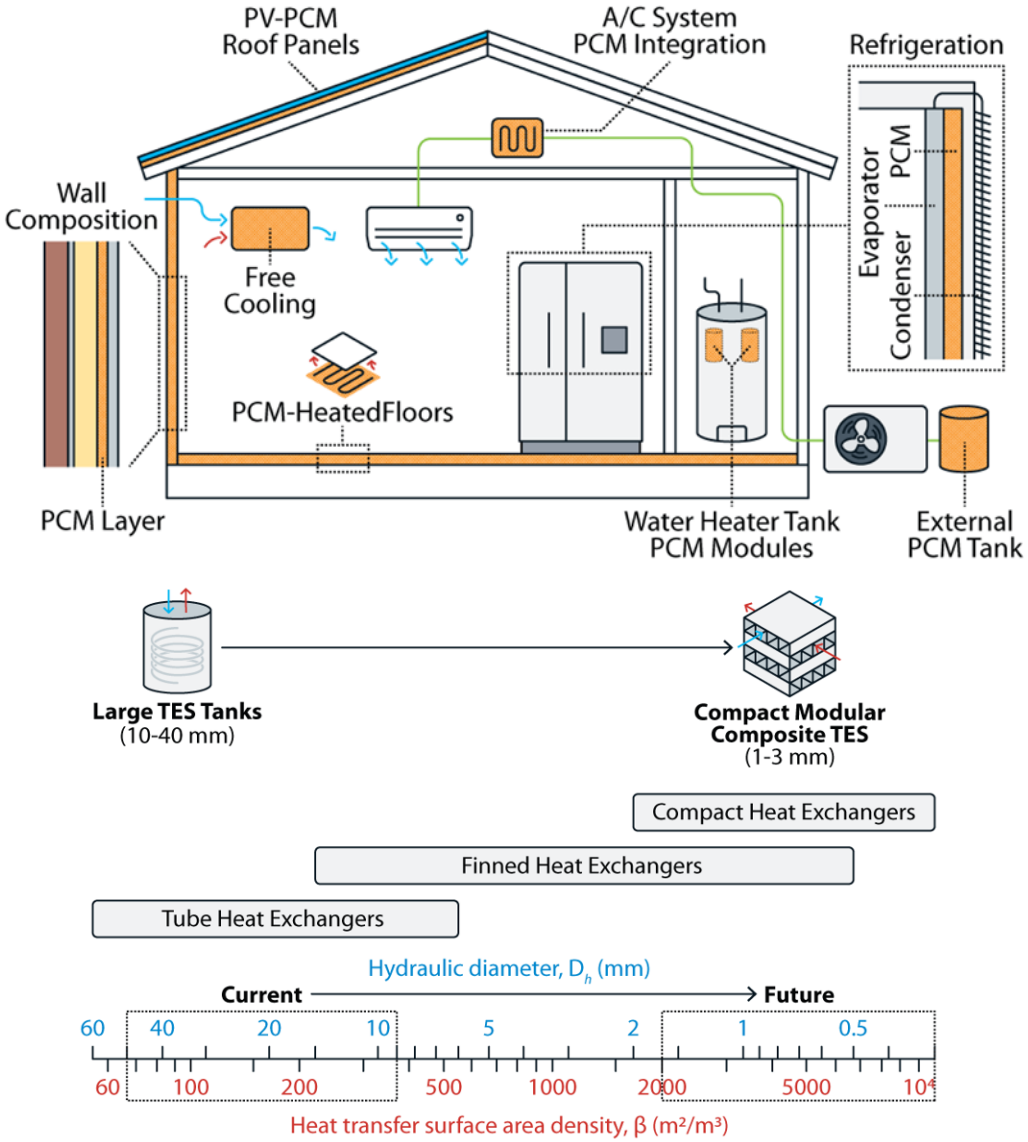
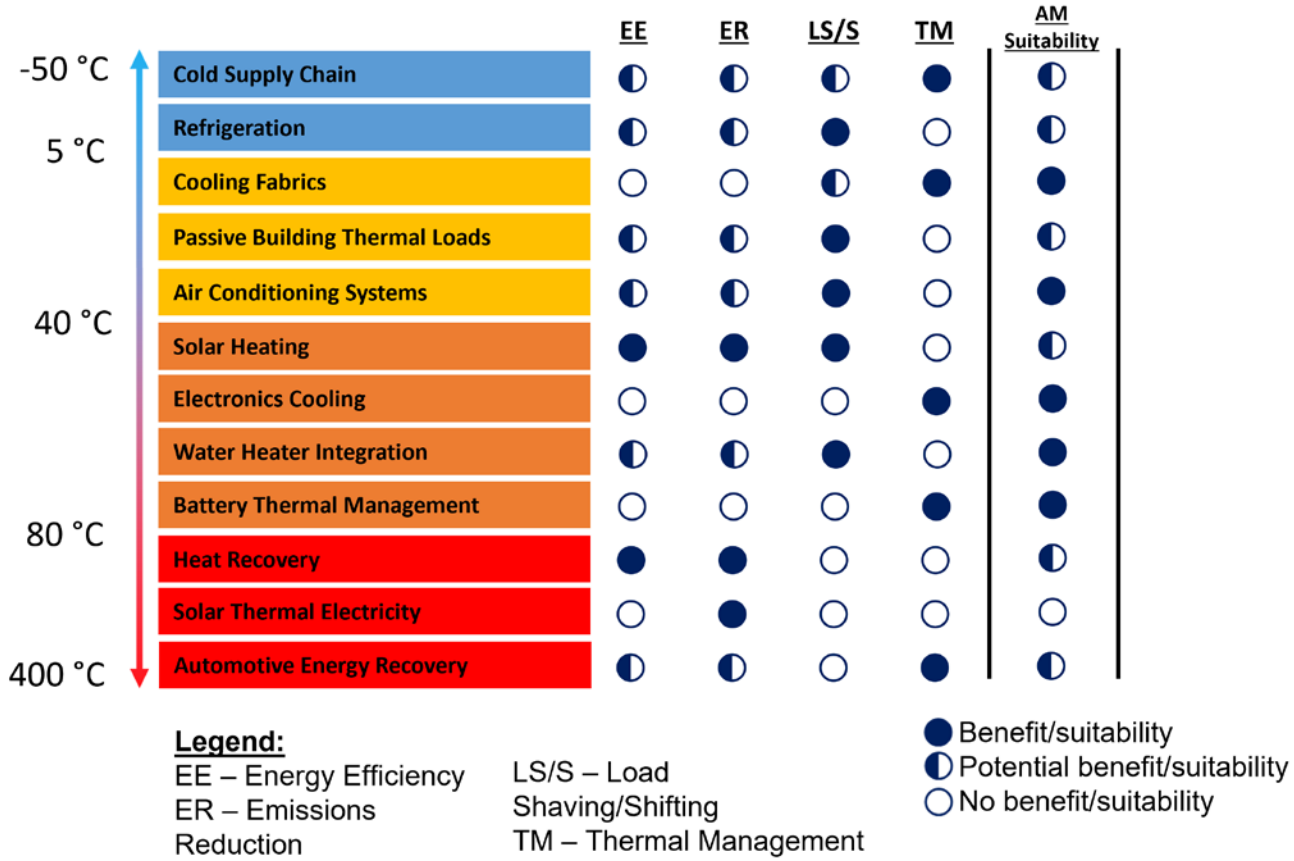
Building Thermal Energy Sciences
National Renewable Energy Lab

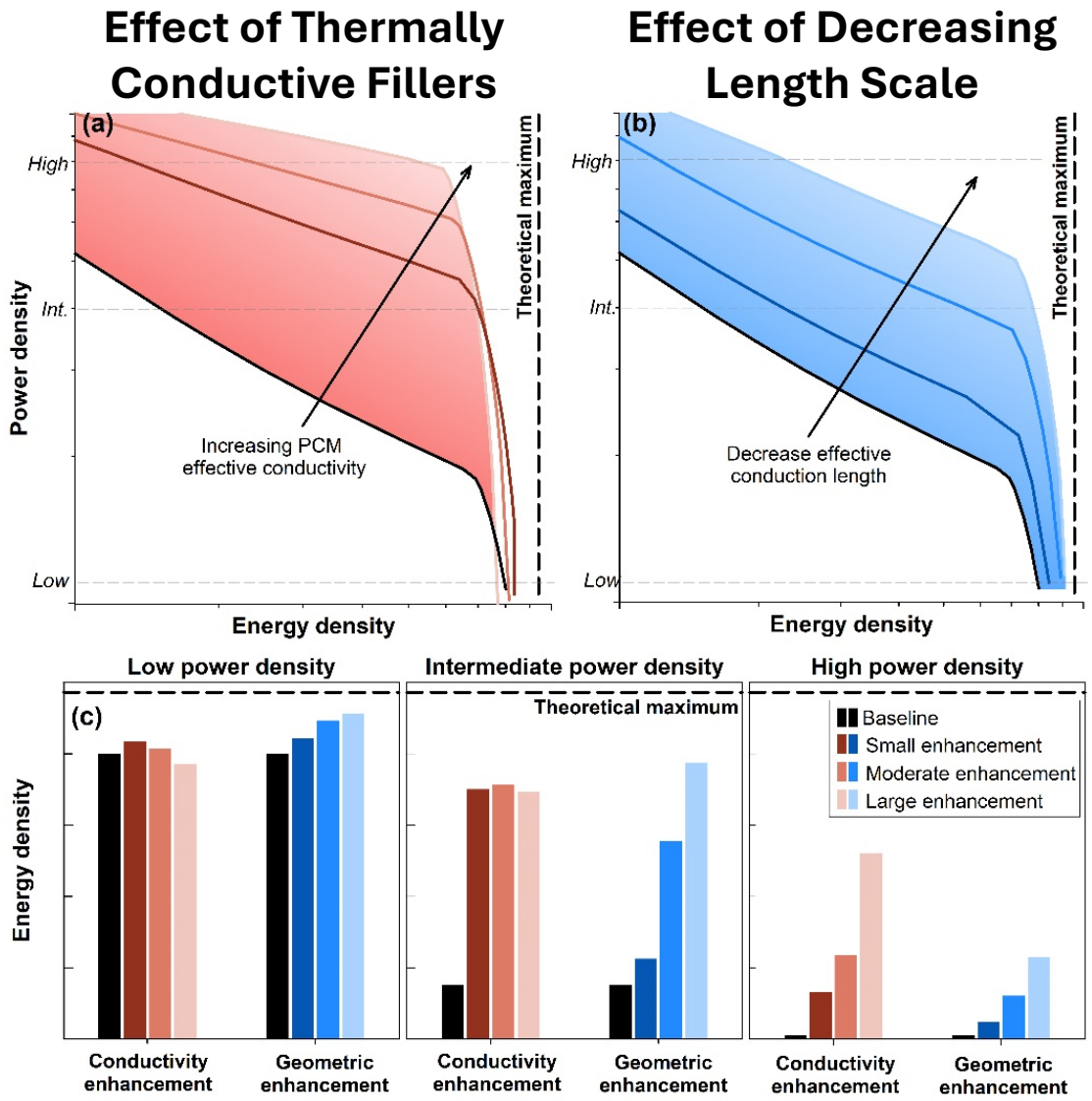
Additive Manufacturing of TES Materials

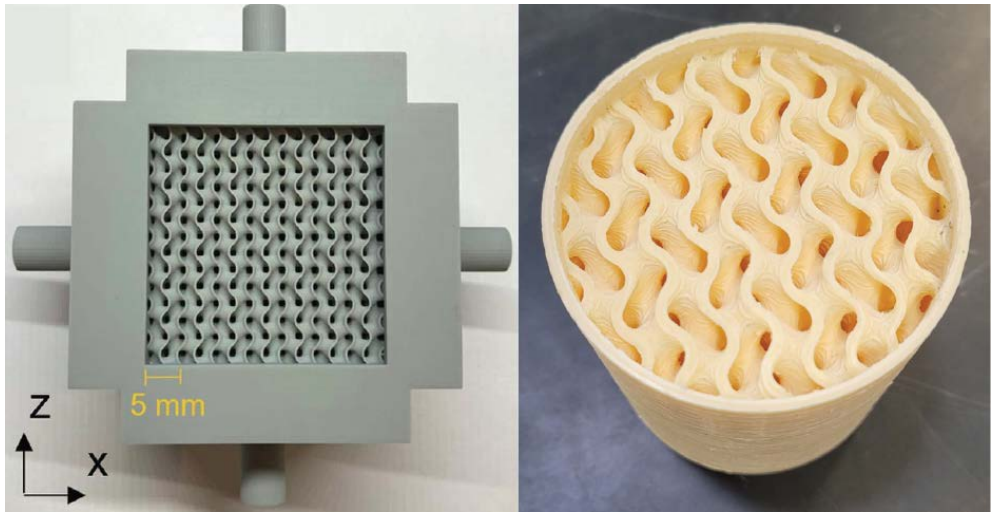




TB Freeman*, KEO Foster*, CJ Troxler, CW Irvin, A Aday, SKS Boetcher, A Mahvi, MK Smith, A Odukomaiya, *Adv. Energy Mater*, 2204208, 2023. DOI: 10.1002/aenm.202204208

Enhancing Capacity and (Dis)Charge





- Ragone plots provide tradeoffs in **energy density** & **power density** for TES or electrochemical systems
  - Design for system power outputs for given applications
- Thermal conductivity enhancements
  - Material compatibility issues and lost capacity
  - Better for high PD needs (emergency cooling systems)
- Decreased conduction lengths
  - Stronger effect at low PD needs (residential heating/ cooling)

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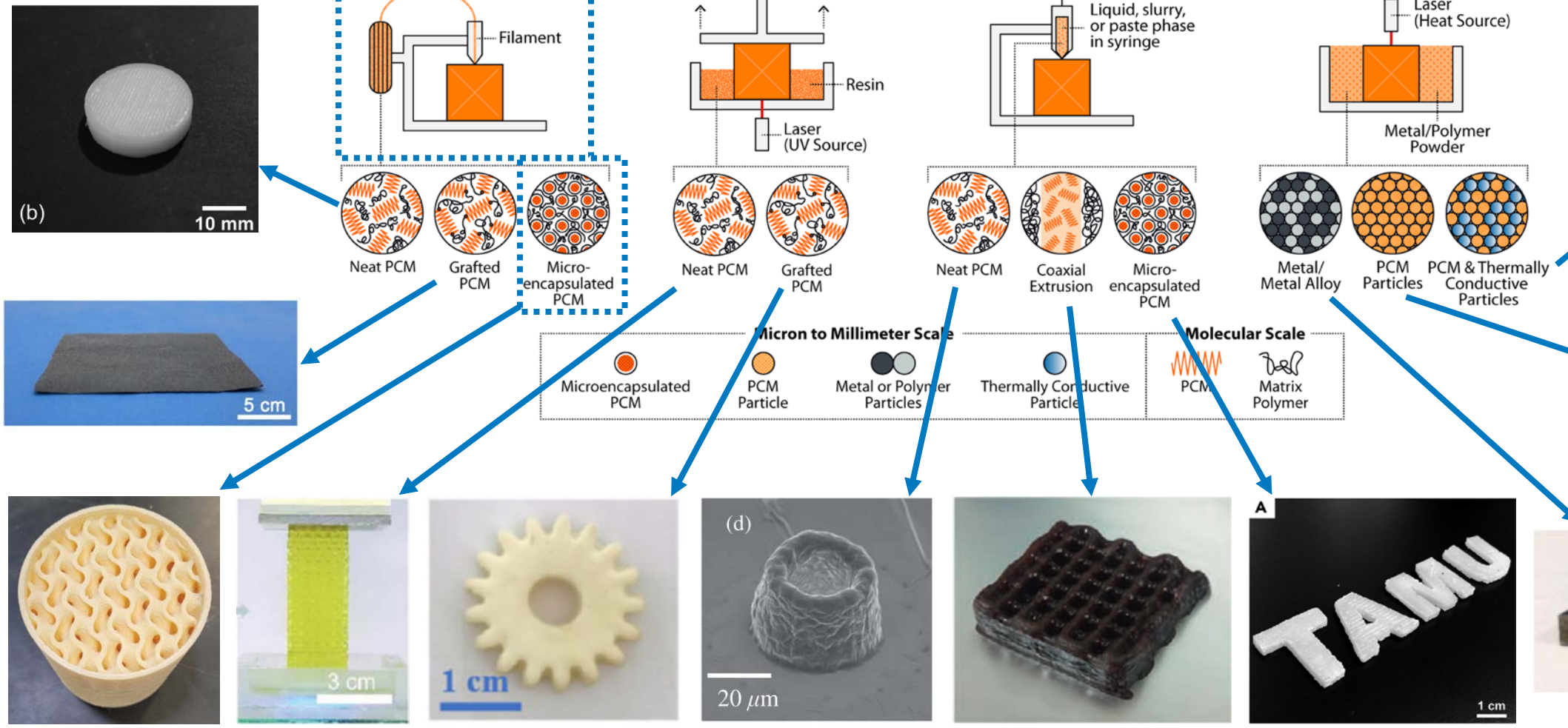
T. Dixit, E. Al-Hajri, M. C. Paul, P. Nithiarasu, S. Kumar, Appl. Therm. Eng. 2022, 210, 118339. P. Singh, A. Odukomaiya, M. K. Smith, A. Aday, S. Cui, A Mahvi, J. Energy Storage 2022, 55, 105581.

Additive Manufacturing of TES Materials

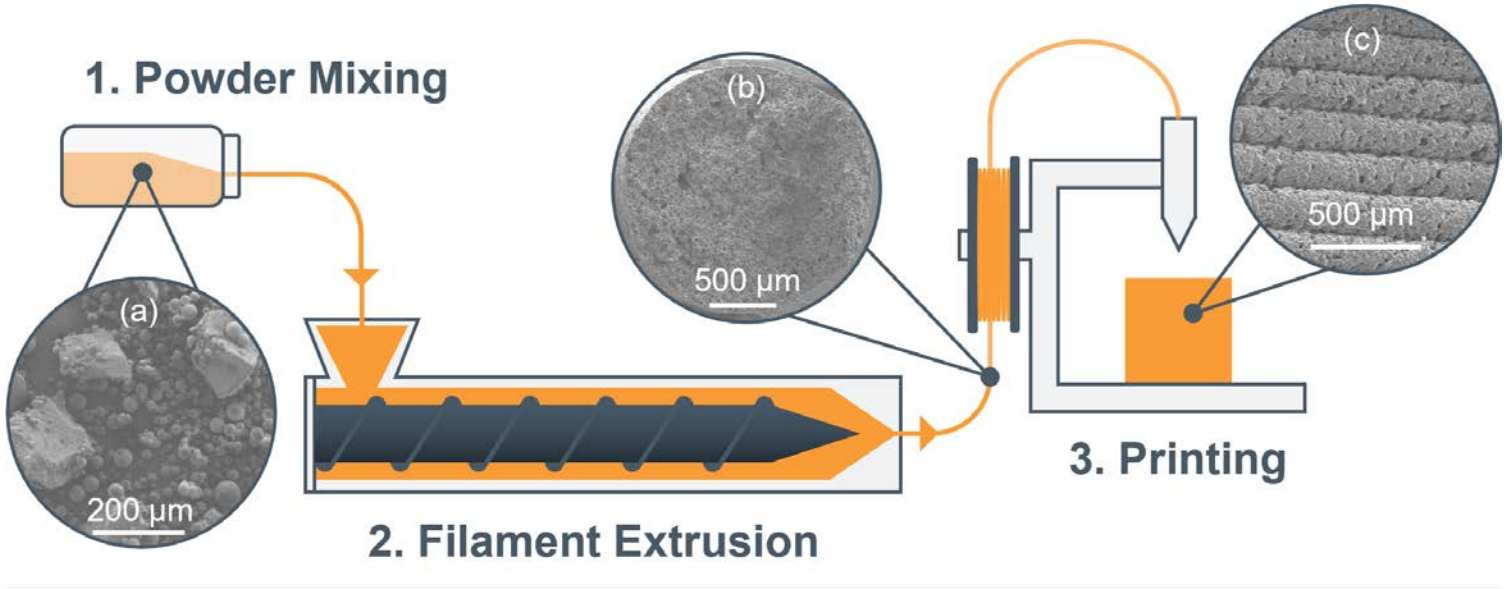
Integration of PCMs into AM Materials and Processes



Freeman TB*, Foster KEO*, *Adv. Energy Mater*, **2023**, 2204208. Freeman, TB, *Add. Manuf.* **2021**, *39*, 101839. Yang, Z, *ACS Appl. Mater. Interfaces* **2022**, *14* (5), 7283–7291. Singh P, *J. Energy Storage* **2022**, 55, 105581. Gogoi, P, *Nanoscale Adv.* **2020**, *2* (9), 3900–3905. Ma, J, *ACS Appl. Mater. Interfaces* **2022**, *14* (3), 4251–4264. Han, Y, *Manufacturing Letters* **2014**, *2* (4), 96–99. Yang, Z, *Small* **2021**, 17 (30), 2101093. Wei, P, *Matter* **2021**, 4 (6), 1975–1989. Sharar, D, Itherm, IEEE: Orlando, FL, **2020**; pp 821–826. Wilts, EM, VA Polytech. Insti., Blacksburg, VA, **2020**. Nofal, M, *J. of Manuf. Proc.* **2019**, 11.

High-Capacity TES Materials

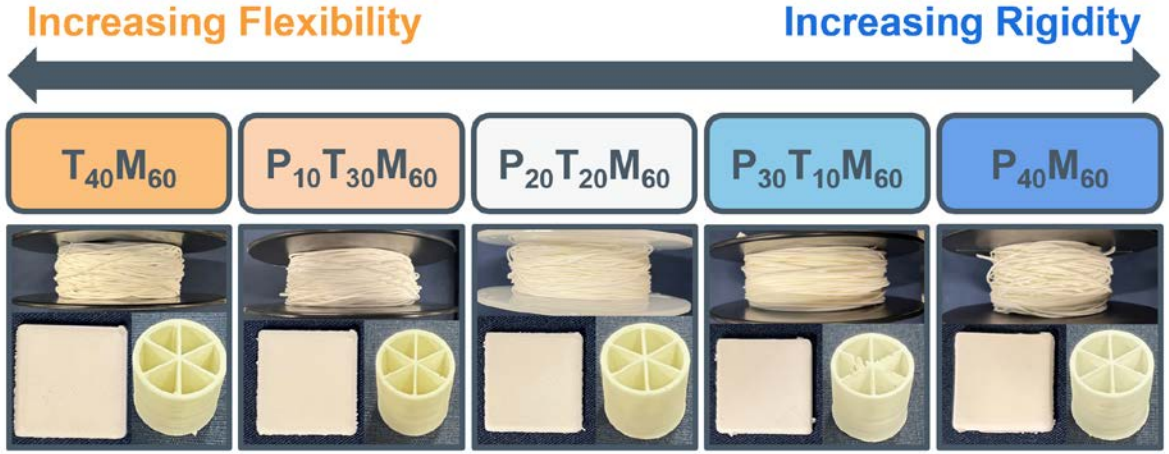
TPU (T): Thermoplastic Polyurethane
PCL (P) : Polycaprolactone
MEPCM (M): Microencapsulated PCM



Material	Avg Size µm	T_m °C	ΔH J/g
PCL powder	200–400	50	75.5
TPU powder	20–80	107	n/a
6D MEPCM	20	6	183

Pros
High MEPCM Loading
Smooth filament surface

Cons
Ripped by gears
Erratic filament thickness

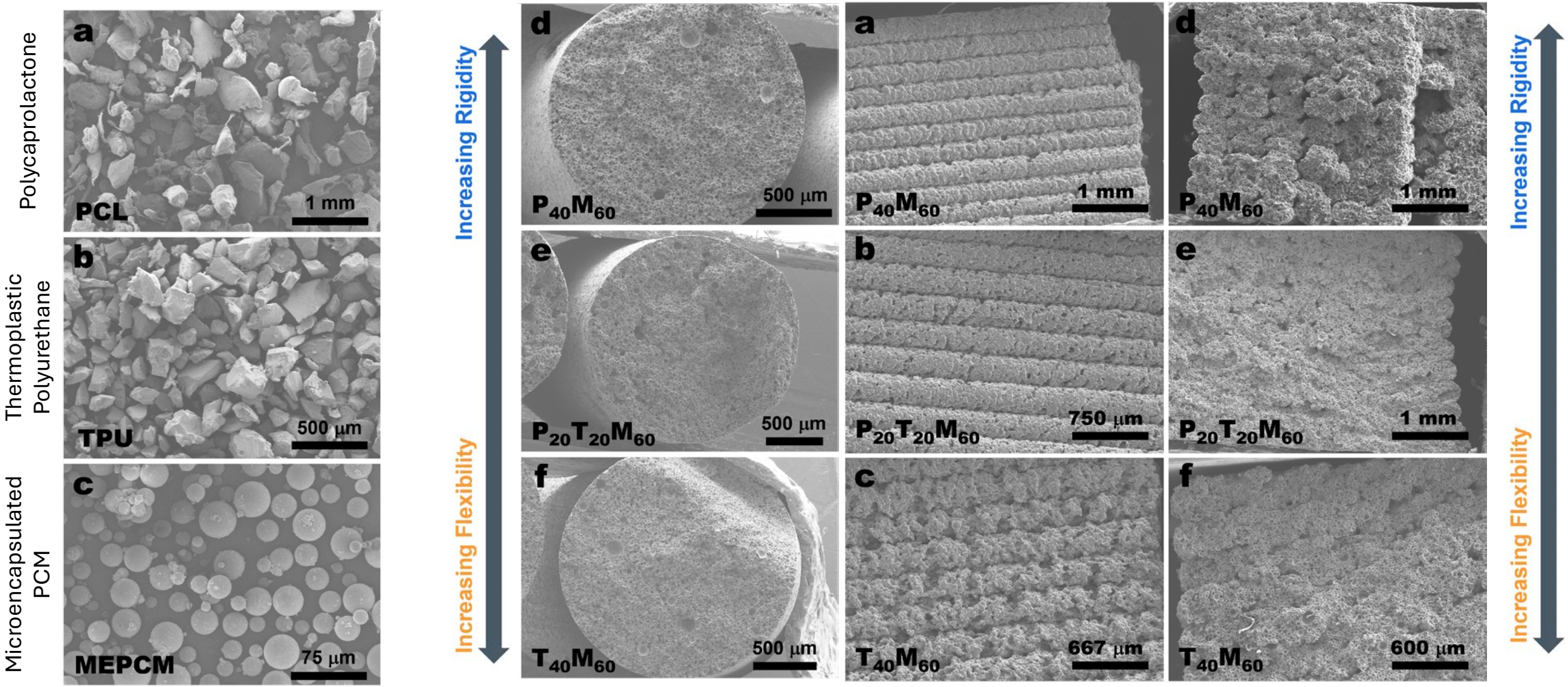


Pros
High MEPCM Loading
Reliable printing

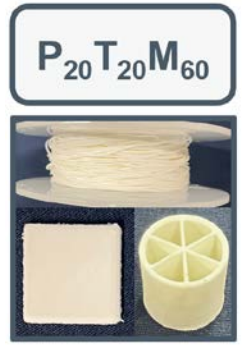
Cons
Rough filament surface
Extremely brittle

Maximum Packing and Optimized Extrusion

Constituent Materials



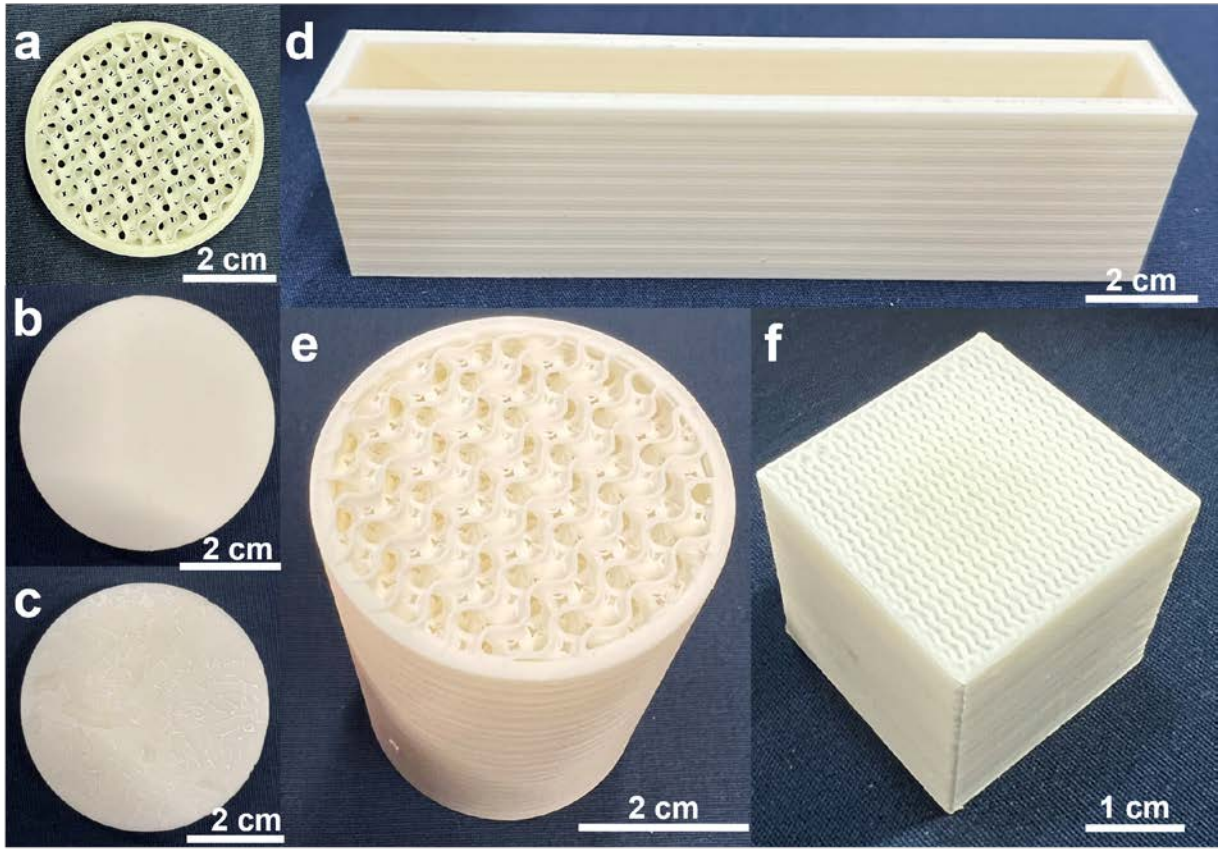
High-Resolution, Geometric Freedom



100% solid wall

15% gyroid

100% infill

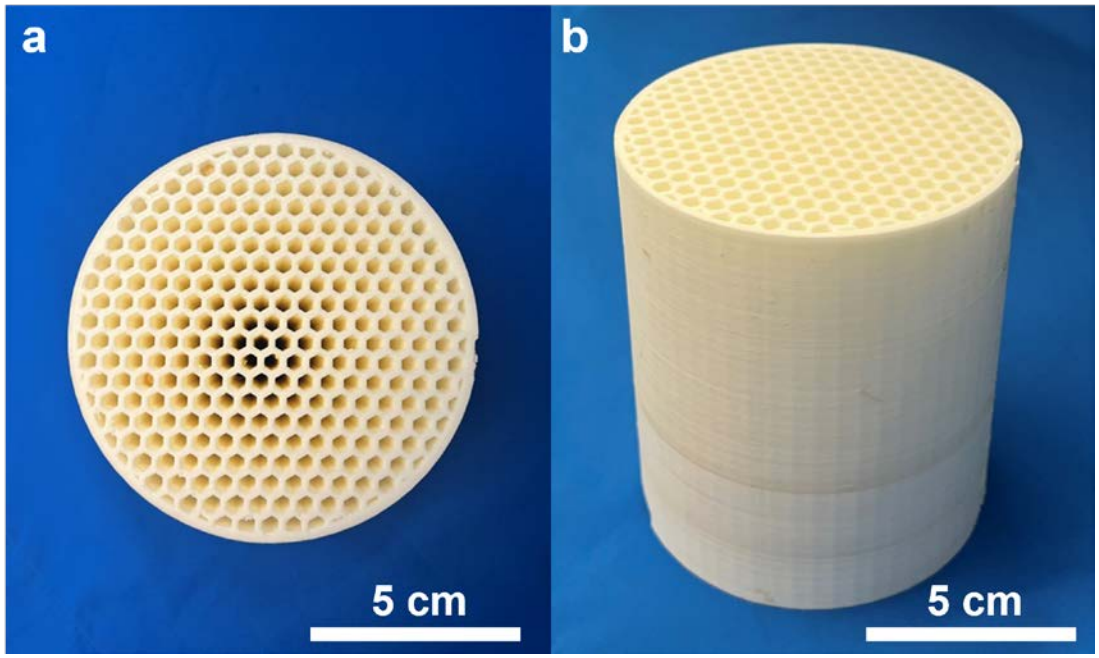


compression molded

15% gyroid

30% gyroid

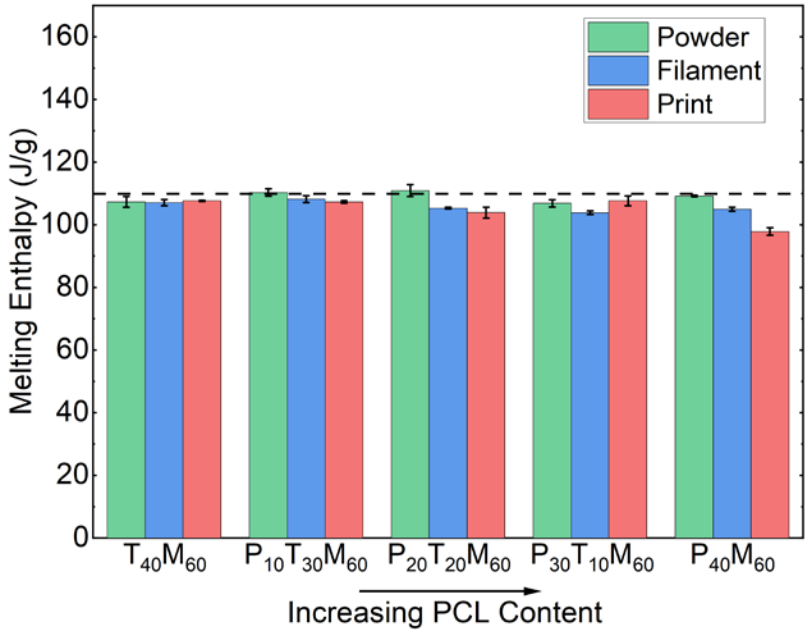
Large Honeycomb Structure



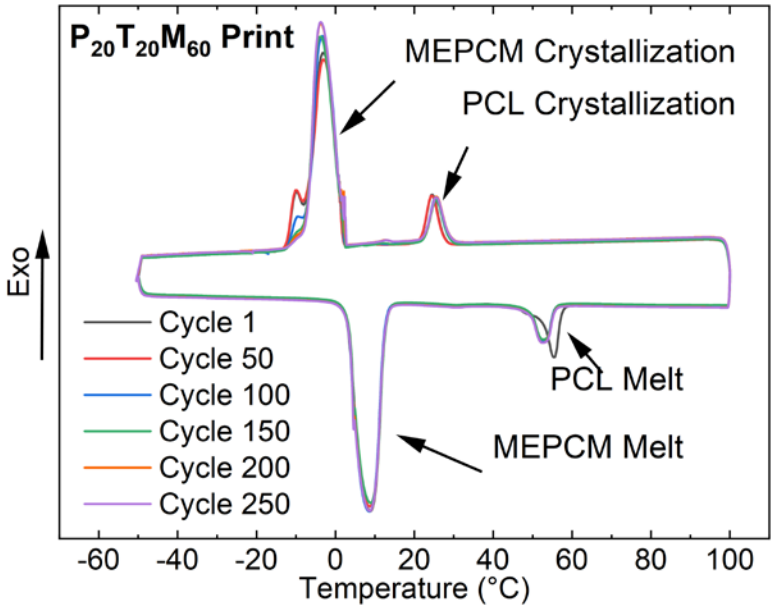
Retaining and Maintaining Thermal Properties

- Limitations in MEPCM incorporation are shear failure of shells
  - TPU and PCL both have high melt flow indices
    - Effectively a lower melt state viscosity
  - Screw extrusion compounding is aggressive

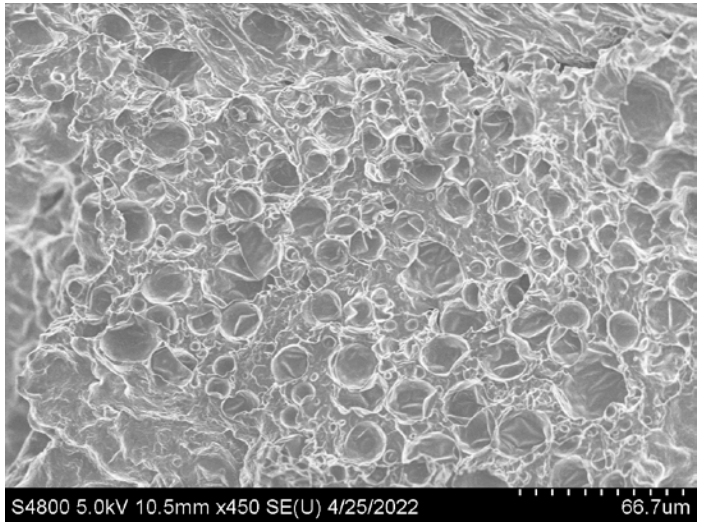
No Loss in TES with Processing



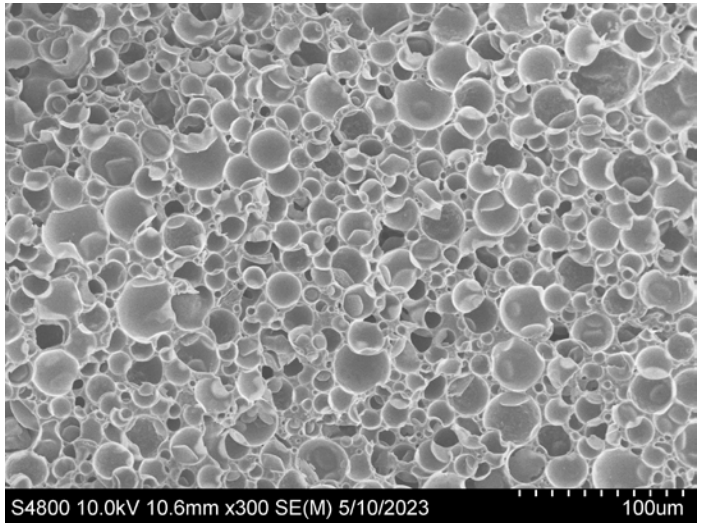
No Loss in TES with Cycling



Poorly Mixed

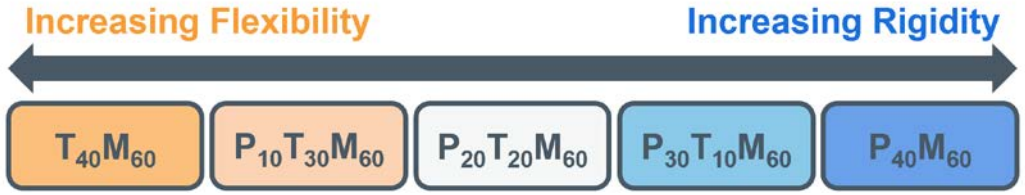


Well Mixed

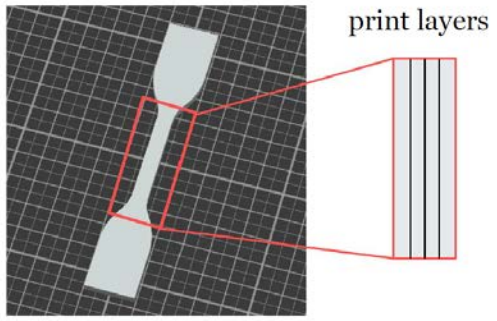


Mechanical Response & Directional Dependence

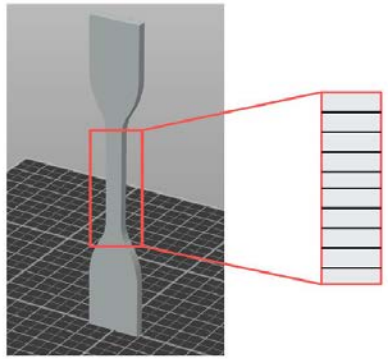
- Fantastic layer adhesion
  - Comparable x- and z-direction data in some cases
  - Elongation compared to molded samples
- Reliable printing made for reliable mechanics
  - No outliers among n = 5 samples
- Balanced properties with blended polymers



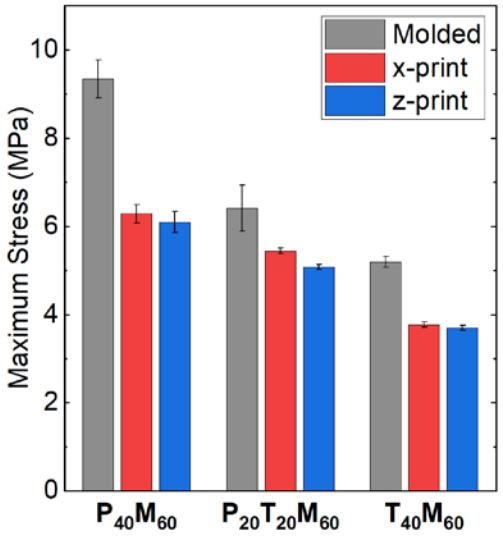
X-direction



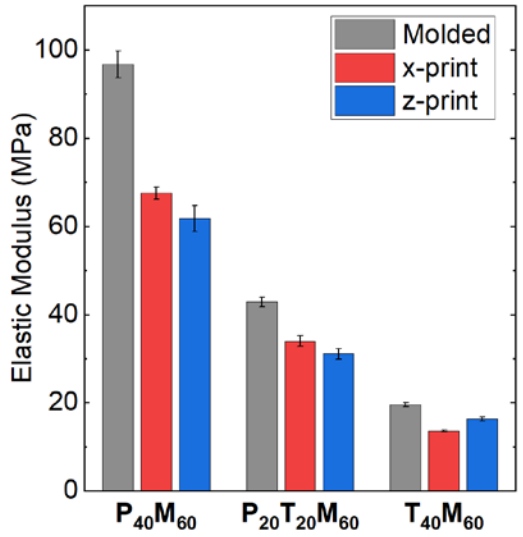
Z-direction



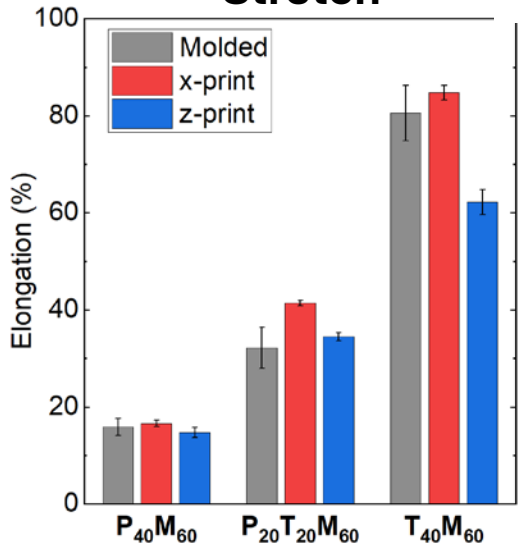
Strength

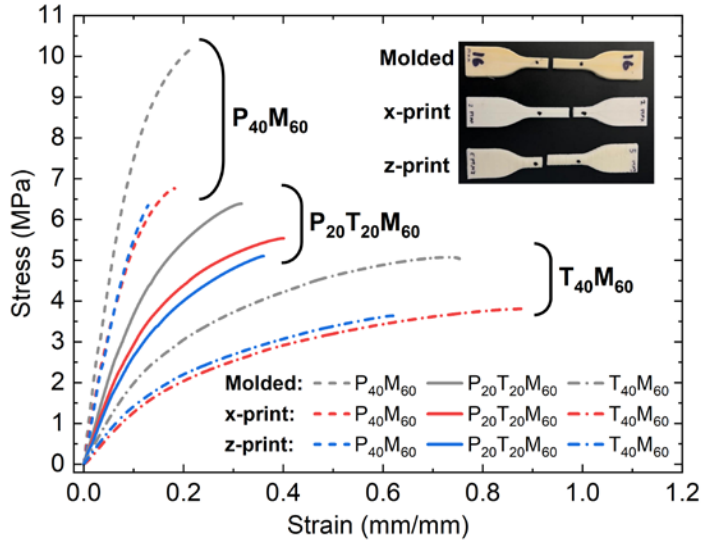


Stiffness



Stretch

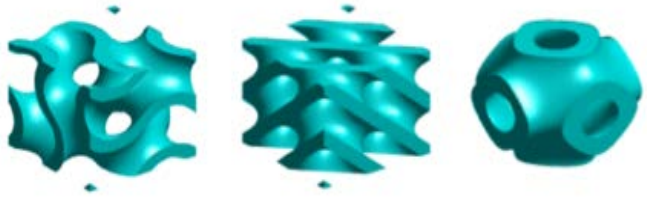


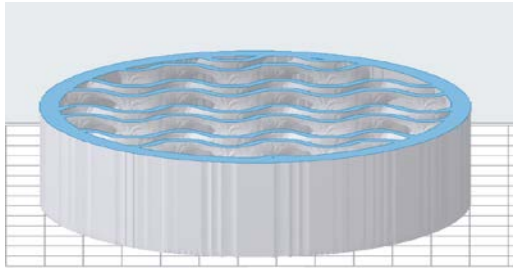


AM-TES Materials Future Directions

- AM-PCM HXC testing in air and water for HVAC and water heating
- Triply periodic minimal surface double walled structures
  - Creating structures with resin printing, but goals to move to laser weld printing

Double-wall Resin 3D Printing → **Wire-Laser Metal 3D Printing**





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Thank you!

Questions?

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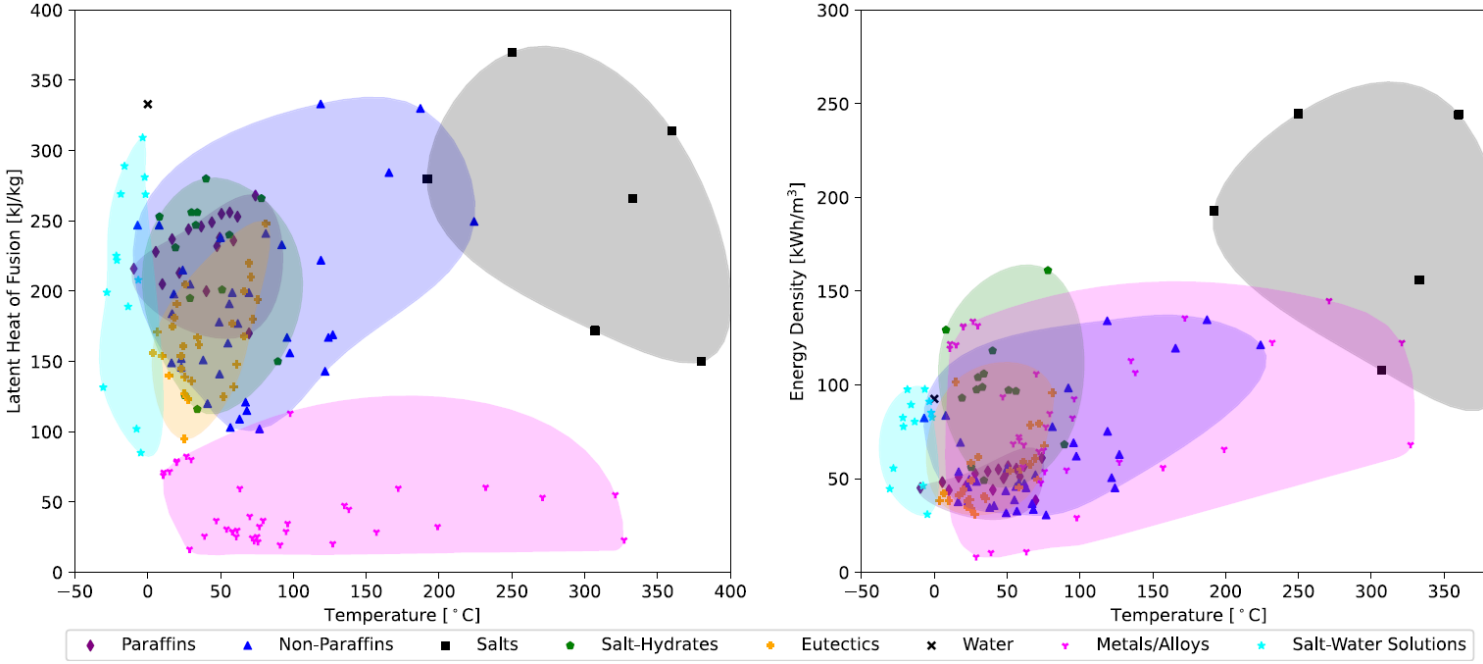

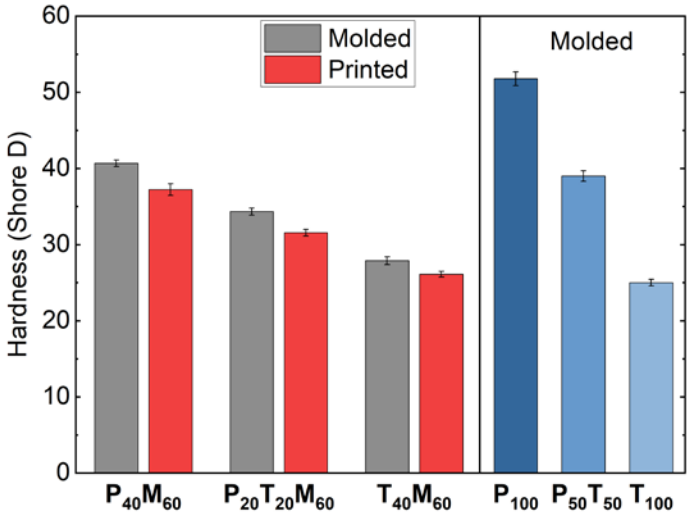

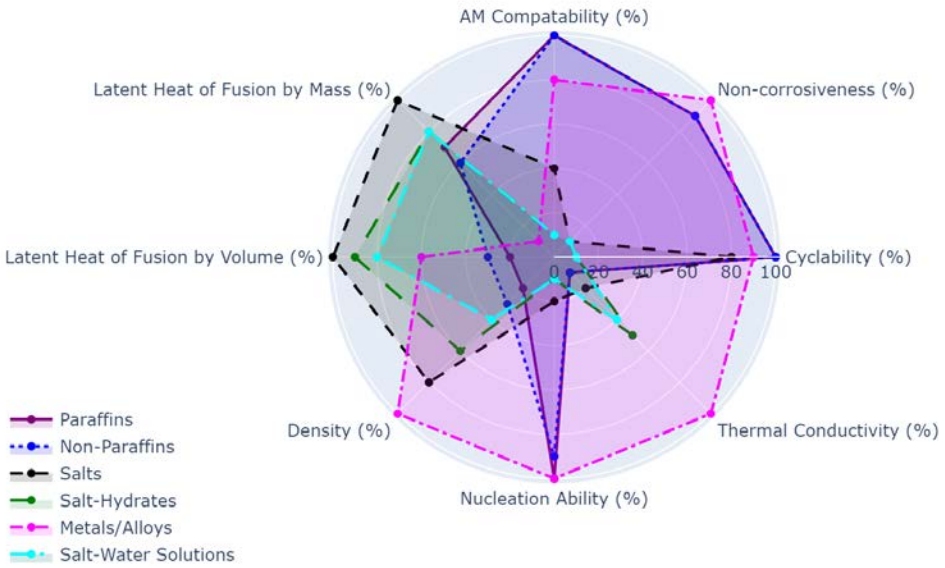

AM-TES Materials Outcomes

Publications

- TB Freeman*, KEO Foster*, CJ Troxler, CW Irvin, A Aday, SKS Boetcher, A Mahvi, MK Smith, A Odukomaiya, "Advanced Materials and Additive Manufacturing for Phase Change Thermal Energy Storage and Management: A Review," *Adv. Energy Mater*, 2204208, 2023. DOI: 10.1002/aenm.202204208
- **KEO Foster**, T Freeman, I Lizier-Zmudzinski, S Dudt, K Morgan, SKS Boetcher, A Odukomaiya, "Additive Manufacturing of Thermal Energy Storage Composites with Microencapsulated Phase Change Materials Supported in a Multi-Polymer Matrix" *Submitted*.
- T Freeman, **KEO Foster**, A Odukomaiya, SKS Boetcher, K Morgan "Fused Filament Fabrication of Thermoplastic Polyurethane Composite with Microencapsulated Phase-Change Material" *In preparation*.

Patents and ROIs

- A Odukomaiya, **KEO Foster**, Thomas Freeman, Matthew Smith, Alliance for Sustainable Energy LLC, 2023. Microencapsulated Phase Change Material Composite for Additive Manufacturing, ROI-23-75, Provisional Application No. 63/507,171, 2023
- A Odukomaiya, **KEO Foster**, Polymer Composite Heat Exchanger for PCM Applications and Method of Fabrication, ROI-22-74