P/O/E/T/S

CENTER FOR POWER OPTIMIZATION OF
ELECTRO-THERMAL SYSTEMS

Novel Materials and Approaches for High Power and Energy Density Thermal Energy Storage

2022 Annual Meeting

October 18 – Noon to 2:00pm PDT

Types of Thermal Energy Storage

Sensible Heat
- Energy stored in vibrational modes of molecules (sand, concrete, molten salts, etc.)

Latent Heat
- Energy stored in media as it changes phase (ice/water, etc.) – phase change materials (PCM)

Thermochemical Energy
- Energy stored in chemical bonds of molecules (metal oxides, reversible oxidation, etc.) – typically larger scale storage – not covered here

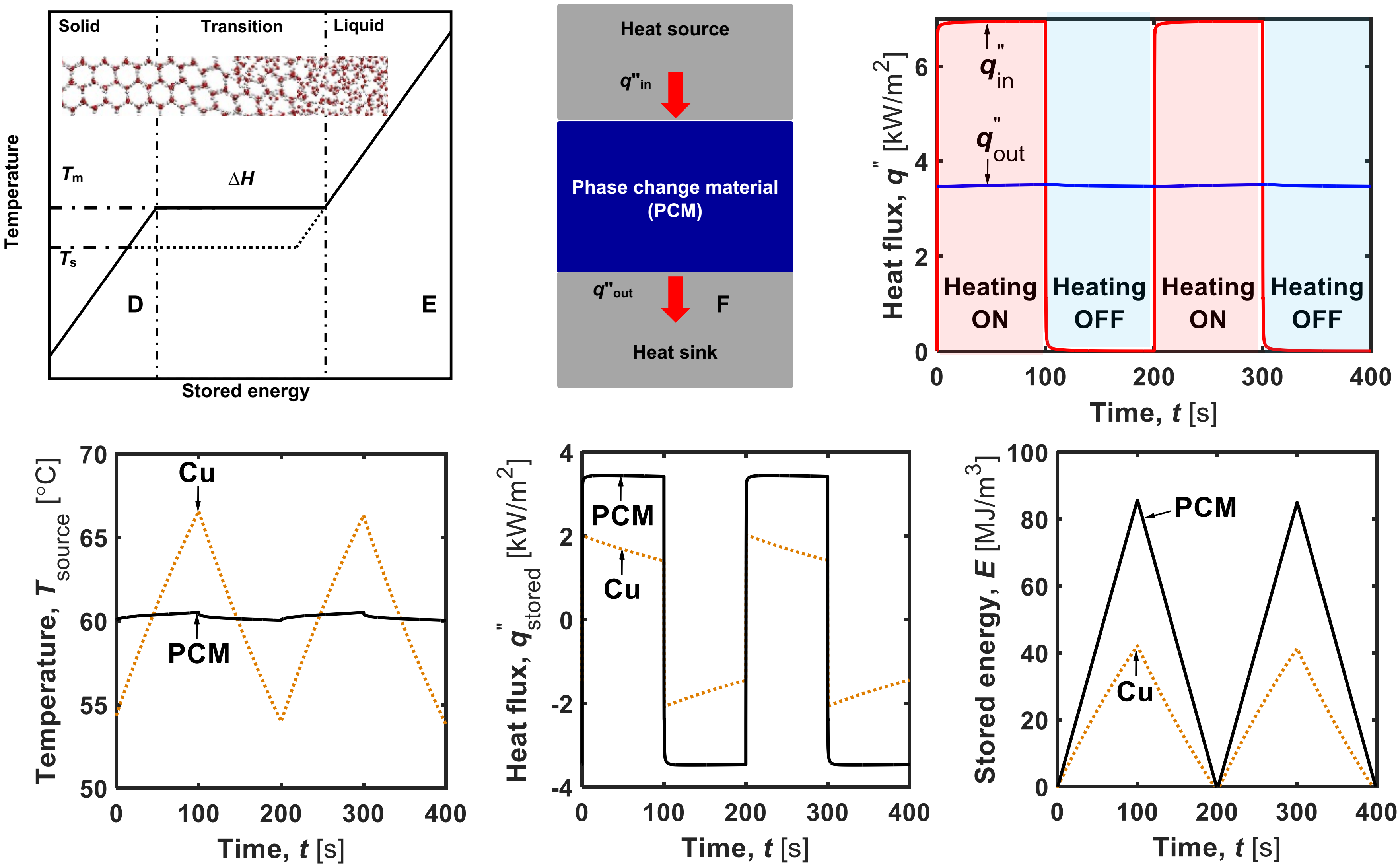

Paraffin


Ice

Advantages
- Potential for very high volumetric and gravimetric energy densities
- Wide and dynamic range of operating temperatures depending on material selection
- Very high exergetic efficiencies, isothermal energy storage and delivery

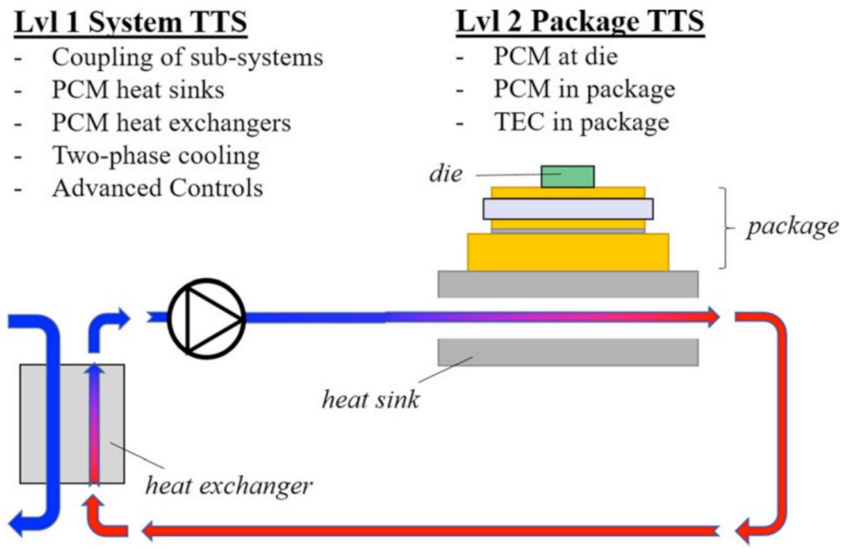
Limitations
- Difficulties maintaining durability of materials over large number of charge/discharge cycles
- Difficulty finding materials which can have both high energy and power density
- Volume change during melting and solidification

Basic Operating Principle

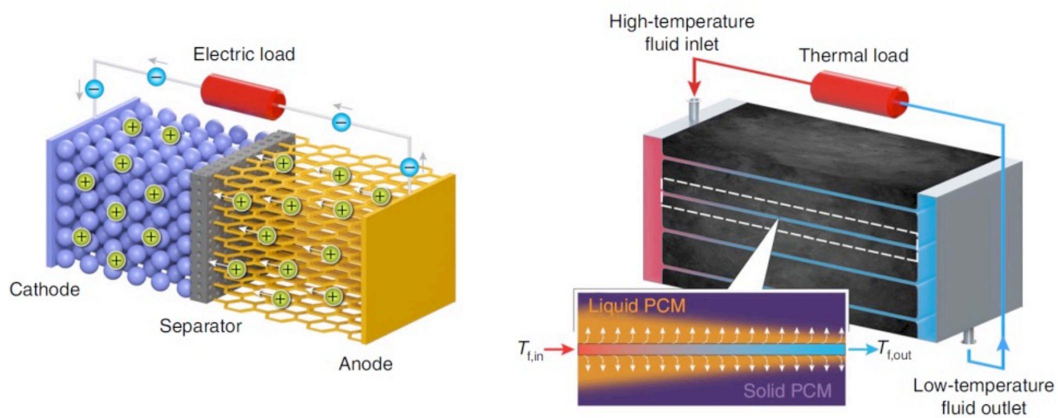


T. Yang, W. P. King, N. Miljkovic, "Phase change material-based thermal energy storage," *Cell Reports Physical Science*, **2**(8), 100540, 2021.

System vs Package Level TES



A System to Package Perspective on Transient Thermal Management of Electronics, JEP, 2020



Rate capability and Ragone plots for phase change thermal energy storage, Nature Energy, 2021

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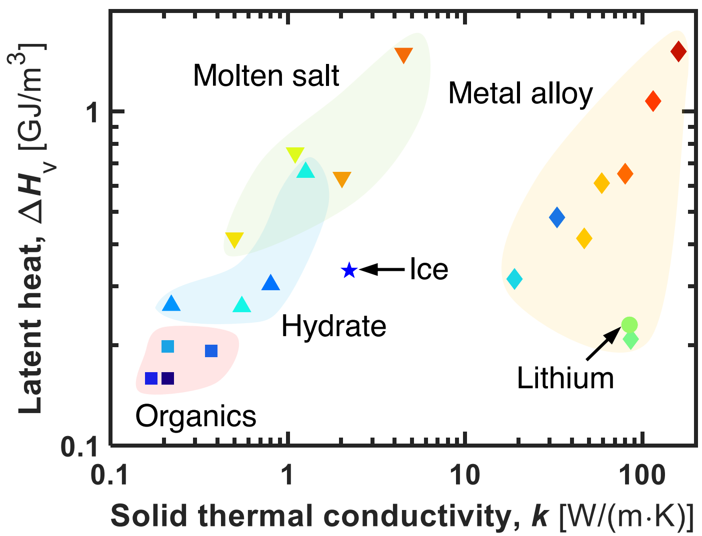
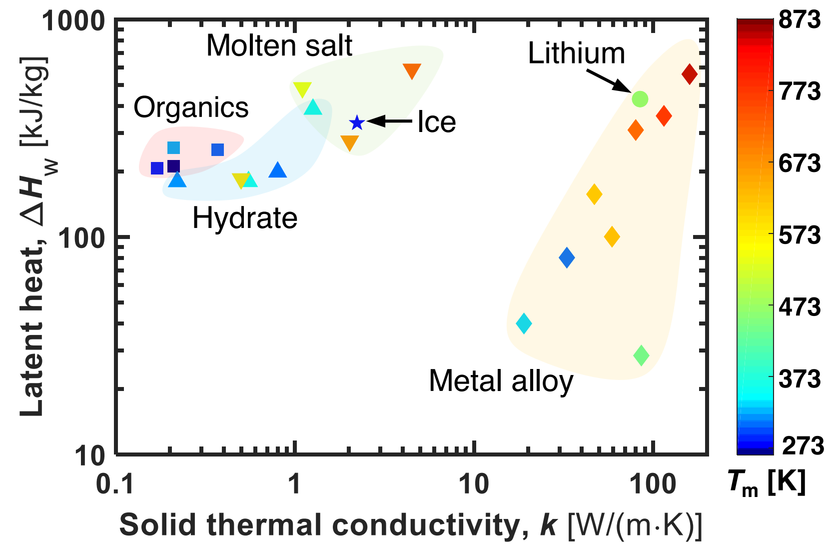
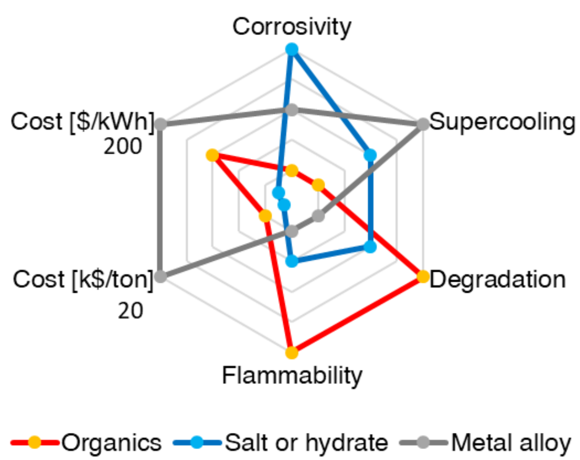
PCM Materials Selection

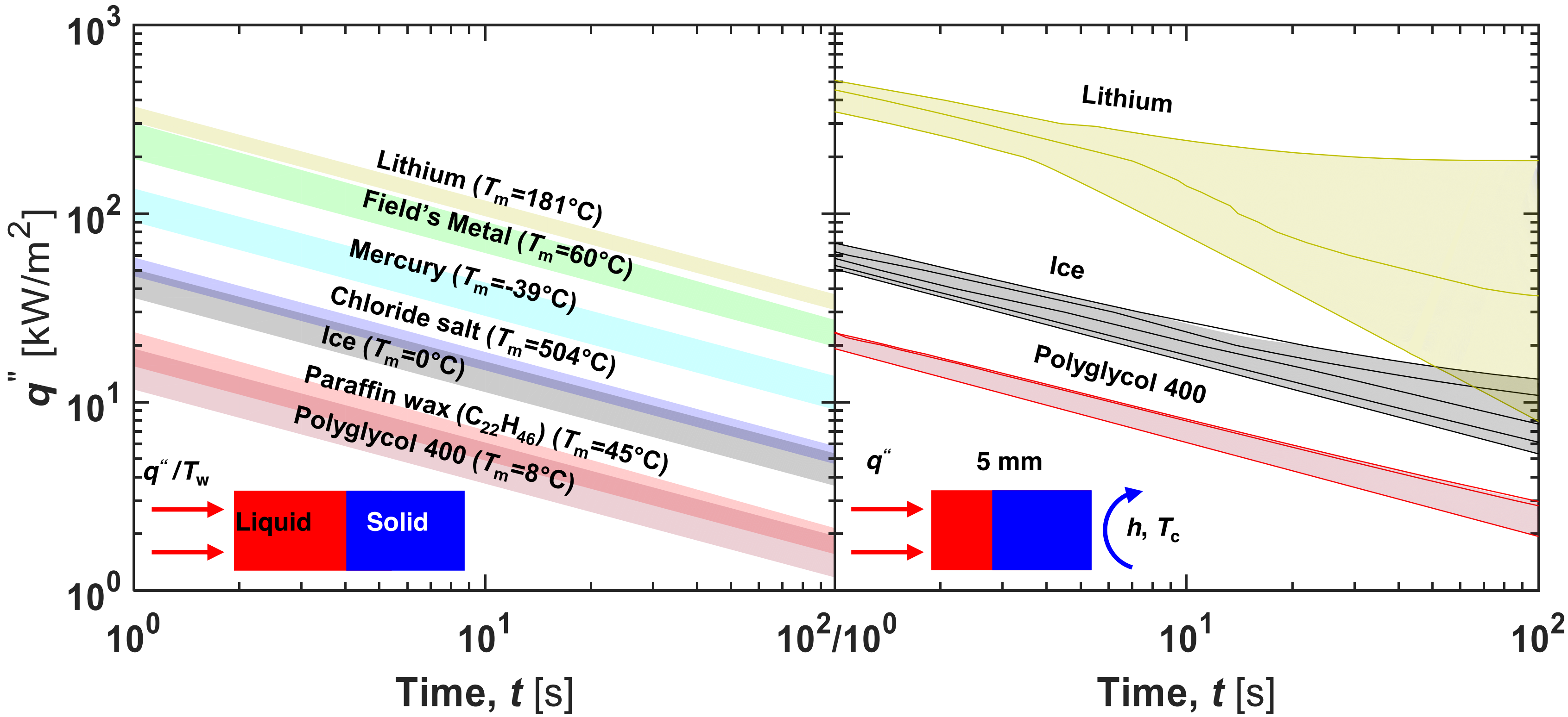






T. Yang, W. P. King, N. Miljkovic, "Phase change material-based thermal energy storage," *Cell Reports Physical Science*, **2**(8), 100540, 2021.

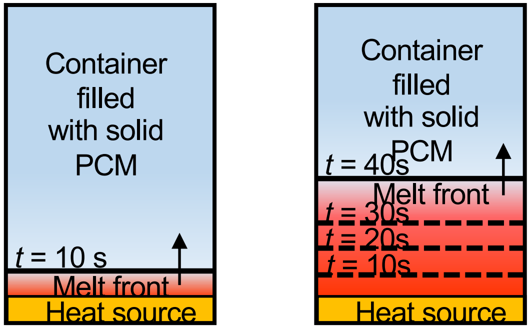
PCM Materials Considerations



- Higher thermal conductivity (k) materials seem to have higher heat fluxes (q'')
- Higher density (ρ) materials seem to have higher heat fluxes (q'')
- As time (t) increases, the heat flux (q'') decreases for all materials

T. Yang, W. P. King, N. Miljkovic, "Phase change material-based thermal energy storage," *Cell Reports Physical Science*, **2**(8), 100540, 2021.

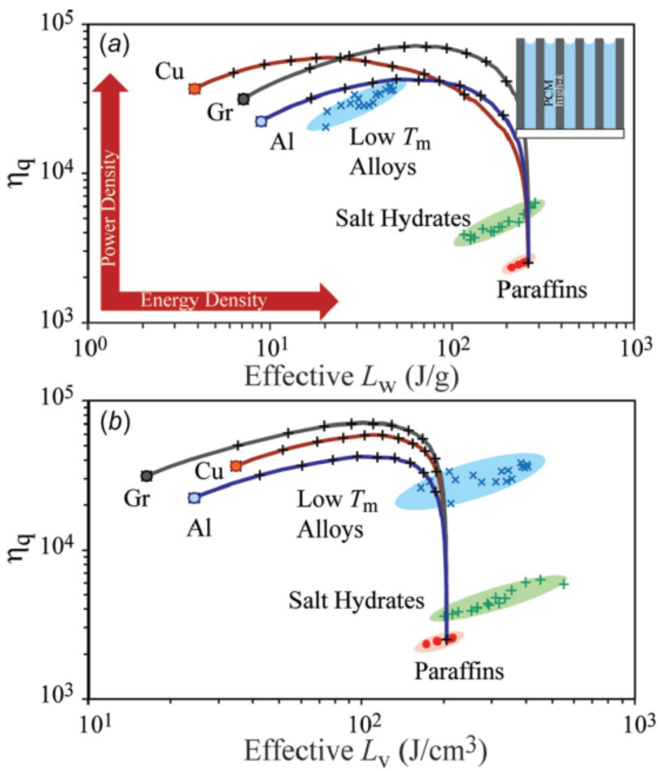
PCM Materials Considerations



L_w = Energy density on mass basis
L_v = Energy density on volume basis
η_q = Cooling power figure of merit

$$\mathrm{FOM}_q = \frac{k_l}{\sqrt{\alpha_l}\ \mathrm{erf}(\lambda_2)} = \frac{\sqrt{k_l \rho_l C_{p,l}}}{\mathrm{erf}(\lambda_2)}$$

Cooling Capacity Figure of Merit for Phase Change Materials, ASME JHT, 2016



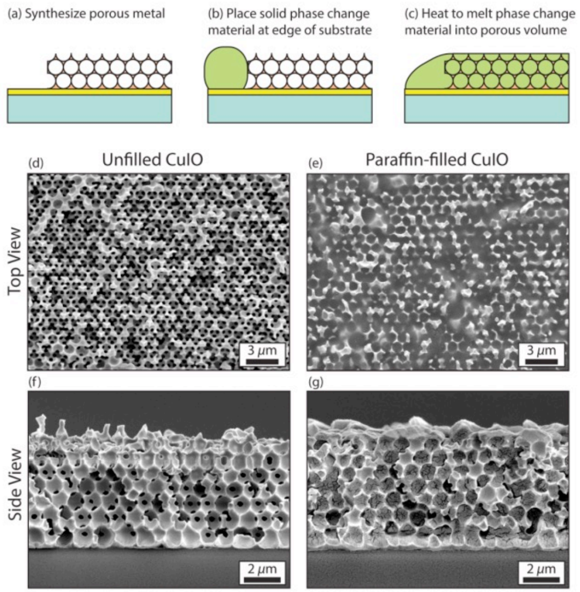
	T_m (°C)	L_w (J g^{-1})	L_v (MJ m^{-3})	k_l (W m^{-1} K^{-1})	ρ_l (g cm^{-3})	FOM$_q$ (W K^{-1} m^{-2} s$^{-0.5}$)
Organics						
Octadecane (paraffin wax)	28.0	244	189	0.15	0.774	2179
Erythritol	120	340	442	0.326	1.30	4894
Salt hydrates						
$KF{\cdot}4H_2O$	18.4	246	357	0.48	1.45	5388
$LiNO_3{\cdot}3H_2O$	30.1	287	408	0.58	1.42	6296
Metal alloys						
Ga	29.8	80.1	488	33.7	6.093	52,153
In	156.6	28.7	201	40	7.01	36,721
Sn	231.9	60.5	425	30	7.03	45,434

[a]Calculated for a dT of 10 °C.

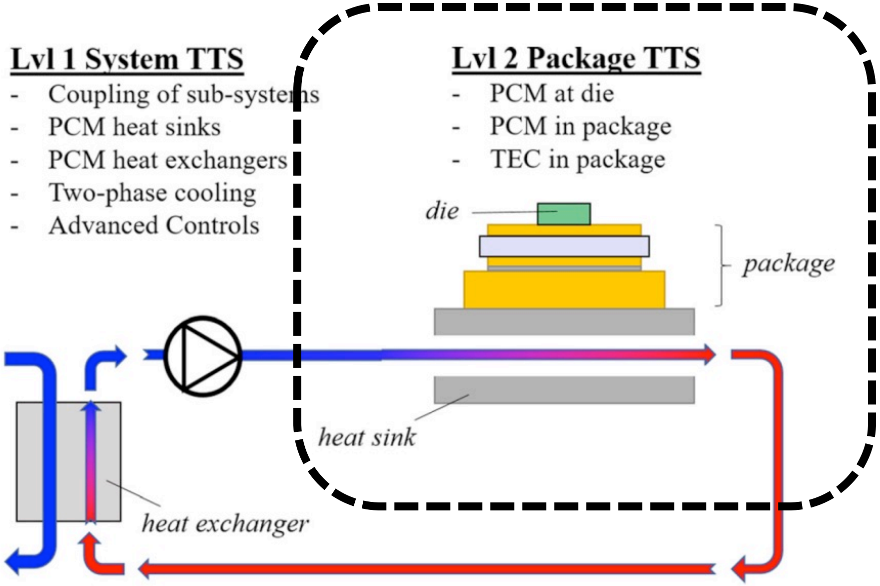
A System to Package Perspective on Transient Thermal Management of Electronics, JEP, 2020

Measurements and Parametric Study of Phase Change Material Integrated Transient Cooling

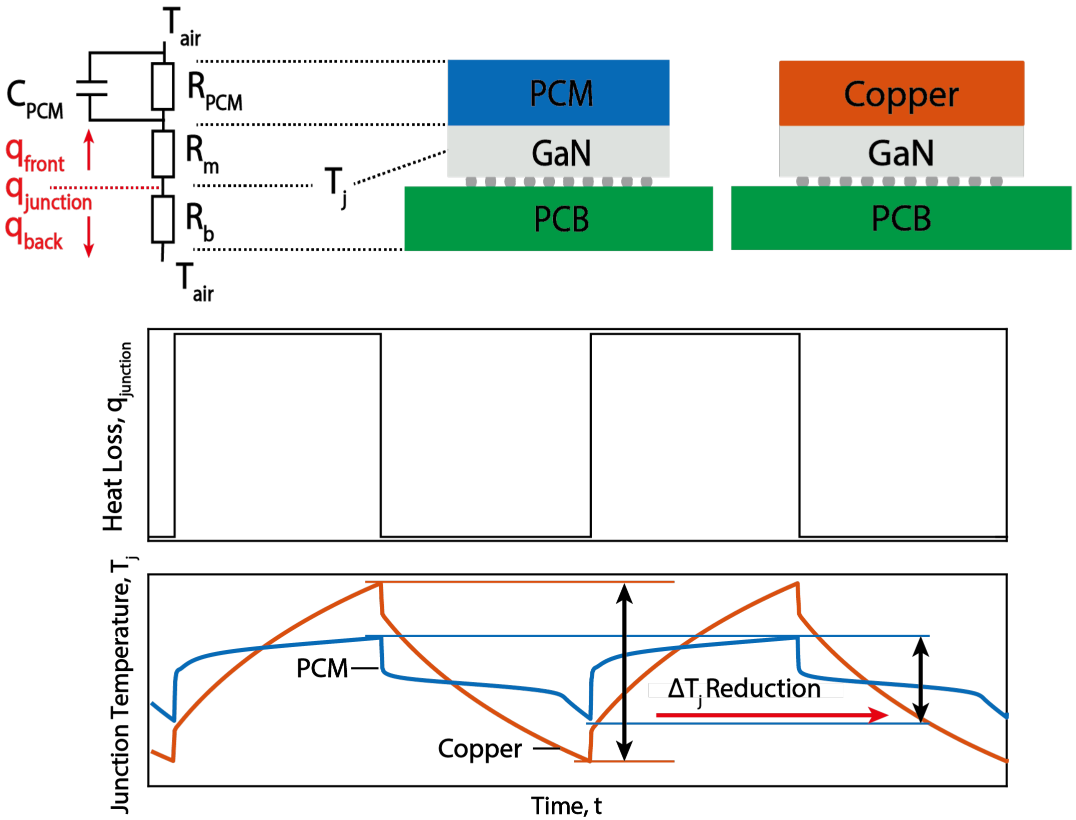
Soonwook Kim, Tianyu Yang, Paul Braun, Nenad Miljkovic, William King, David Huitink, Ken Goodson



Source: J. Appl. Phys. **124**, 145103 (2018)



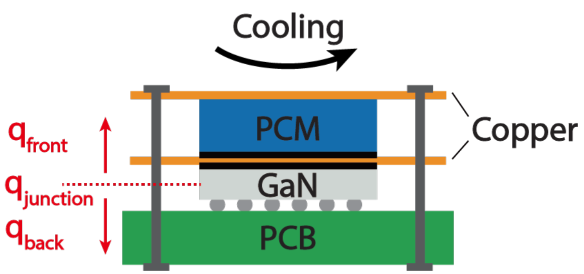
Phase change material transient device cooling

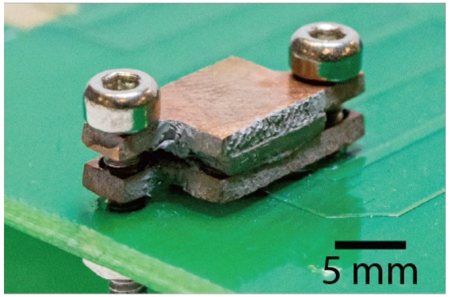


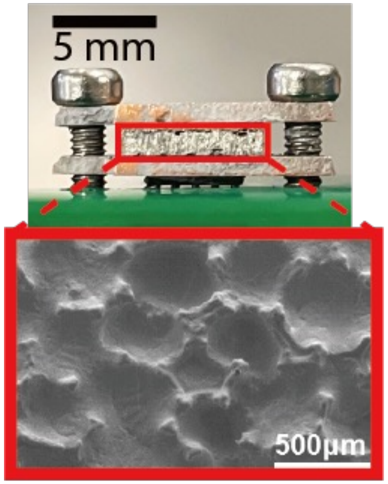
PCMs on cyclic power load operation

Phase change materials **High Latent Heat**	→	Junction temperature swing reduction	→	Enhanced device reliability

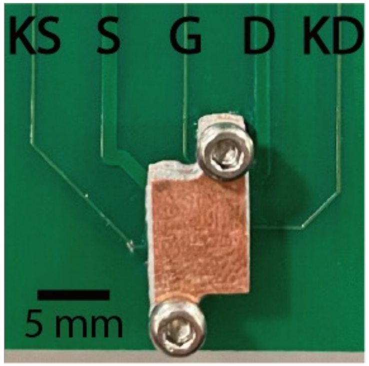
Experiment







Field's metal/Cu foam composite



Device

- Field's metal/Cu foam composite ($T_{\mathrm{melt}} = 60°\mathrm{C}$) integrated with top-cooled GaN device (EPC 2034)

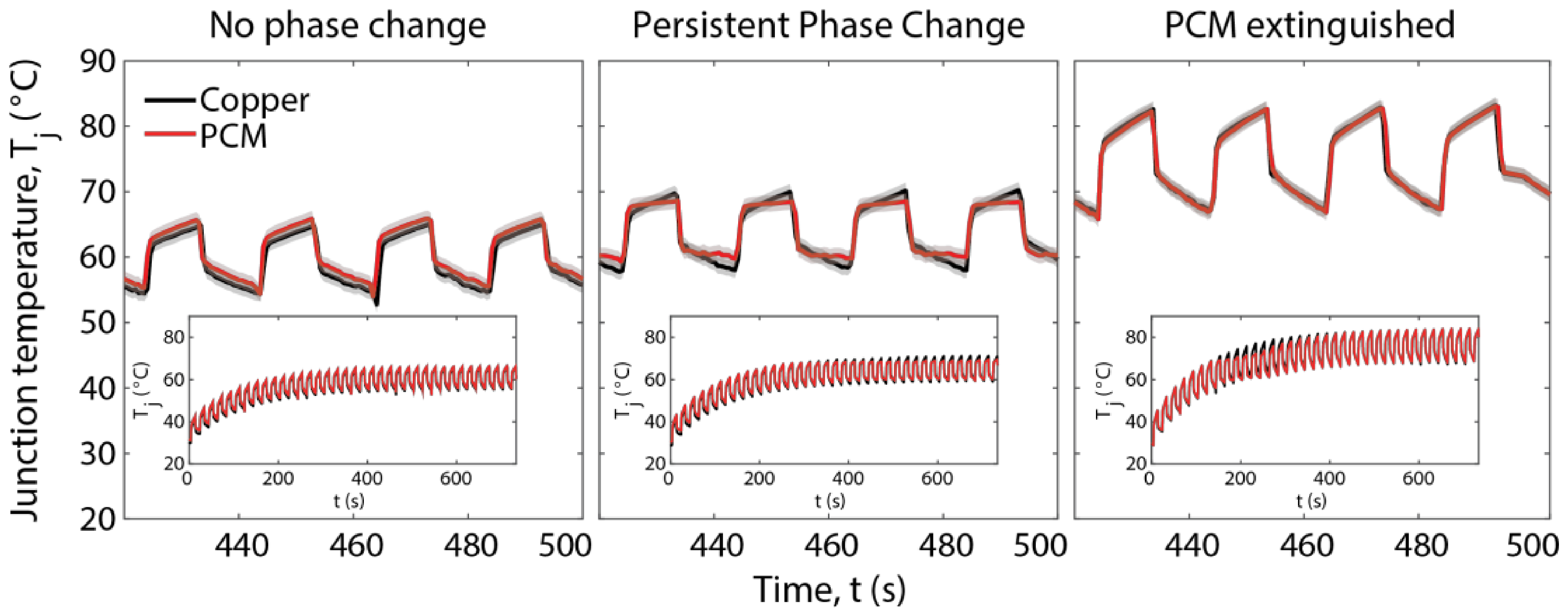
Test samples

- 1.3 mm thick Field's metal/Cu foam composite
- 1 mm thick Copper

Cooling condition

- Fan-driven air forced convection ($\bar{u}$=1.2 m/s)

Repeated pulsing reveals different response behavior



- The relationship between the PCM melting and regeneration rate determines the phase change status

  1) Persisting phase change case: PCM melting rate ≤ PCM regeneration rate

  2) PCM extinguished case: PCM melting rate > PCM regeneration rate

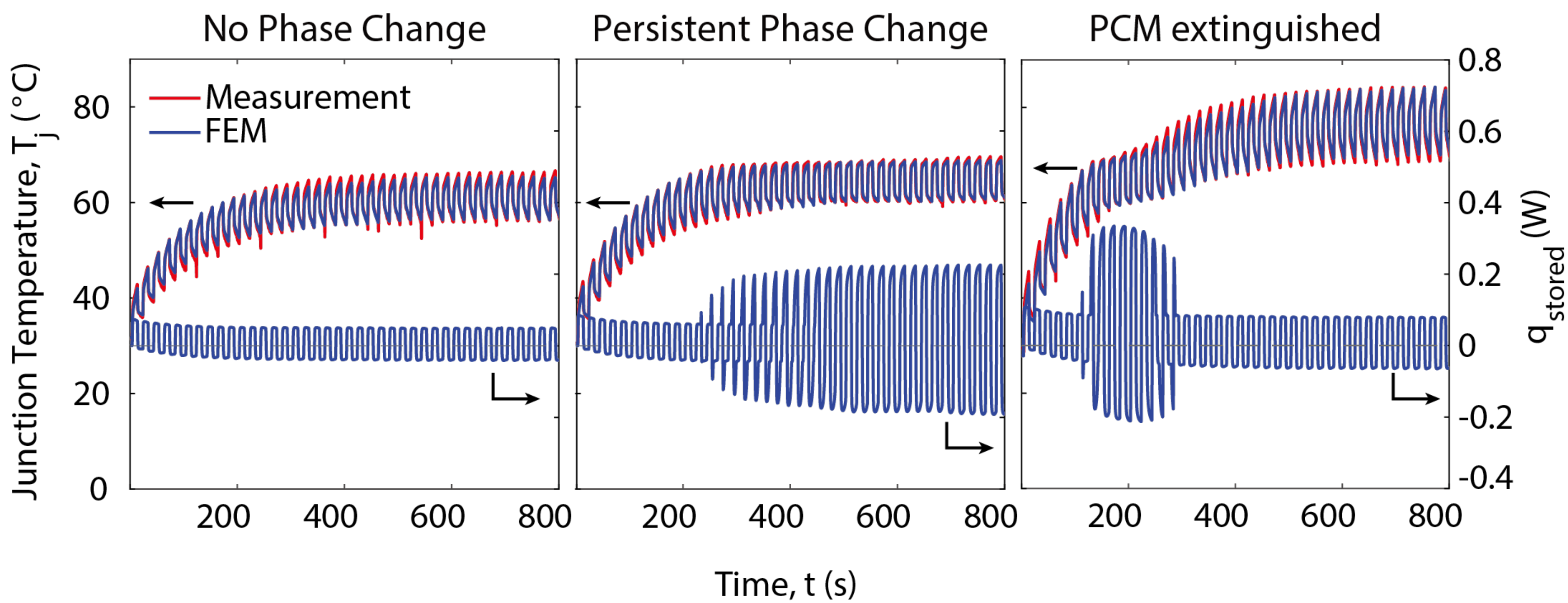
Junction temperature swing reduction

Power loss (W)		1.20	1.40	1.50	1.70	1.90
25% Duty cycle	3 s	-1.72%	-1.75%	-3.81%	-6.33%	-16.50%
	5 s	-0.09%	-0.99%	-0.26%	-12.81%	-18.55%
	10 s	0.10%	0.01%	-0.93%	-9.92%	-14.40%
Power loss (W)		0.70	0.80	0.90	1.00	1.10
50% Duty cycle	3 s	-3.68%	-2.41%	-8.20%	-3.76%	-1.91%
	5 s	-4.86%	-4.16%	-2.39%	-5.45%	-2.47%
	10 s	-2.80%	-0.46%	0.59%	-10.86%	-15.47%
Power loss (W)		0.50	0.60	0.70	0.80	0.90
75% Duty cycle	3 s	-1.14%	-2.08%	-4.85%	-0.87%	-4.20%
	5 s	-3.02%	-5.21%	-5.63%	-3.61%	-3.46%
	10 s	0.21%	-3.60%	-3.64%	-4.38%	-0.95%

: No Phase Change : Persistent Phase Change : PCM extinguished

- Reduction of the temperature swing with respect to copper: $\frac{\Delta T_{j,PCM}-\Delta T_{j,Cu}}{\Delta T_{j,Cu}}$ (%)
- Up to ~20% reduction in junction temperature compared to the copper reference

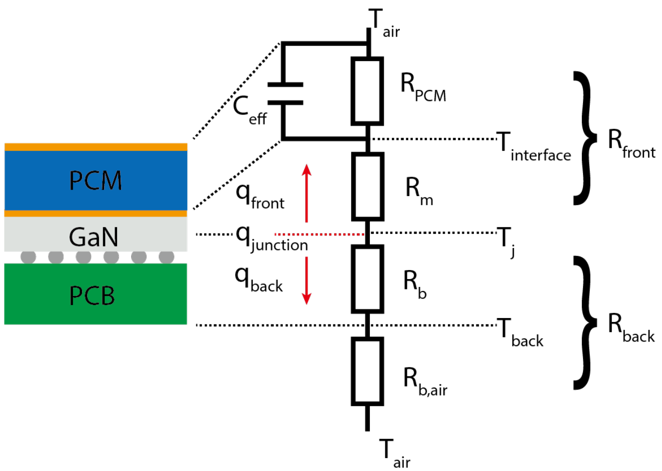
Heat flow depends on phase change status



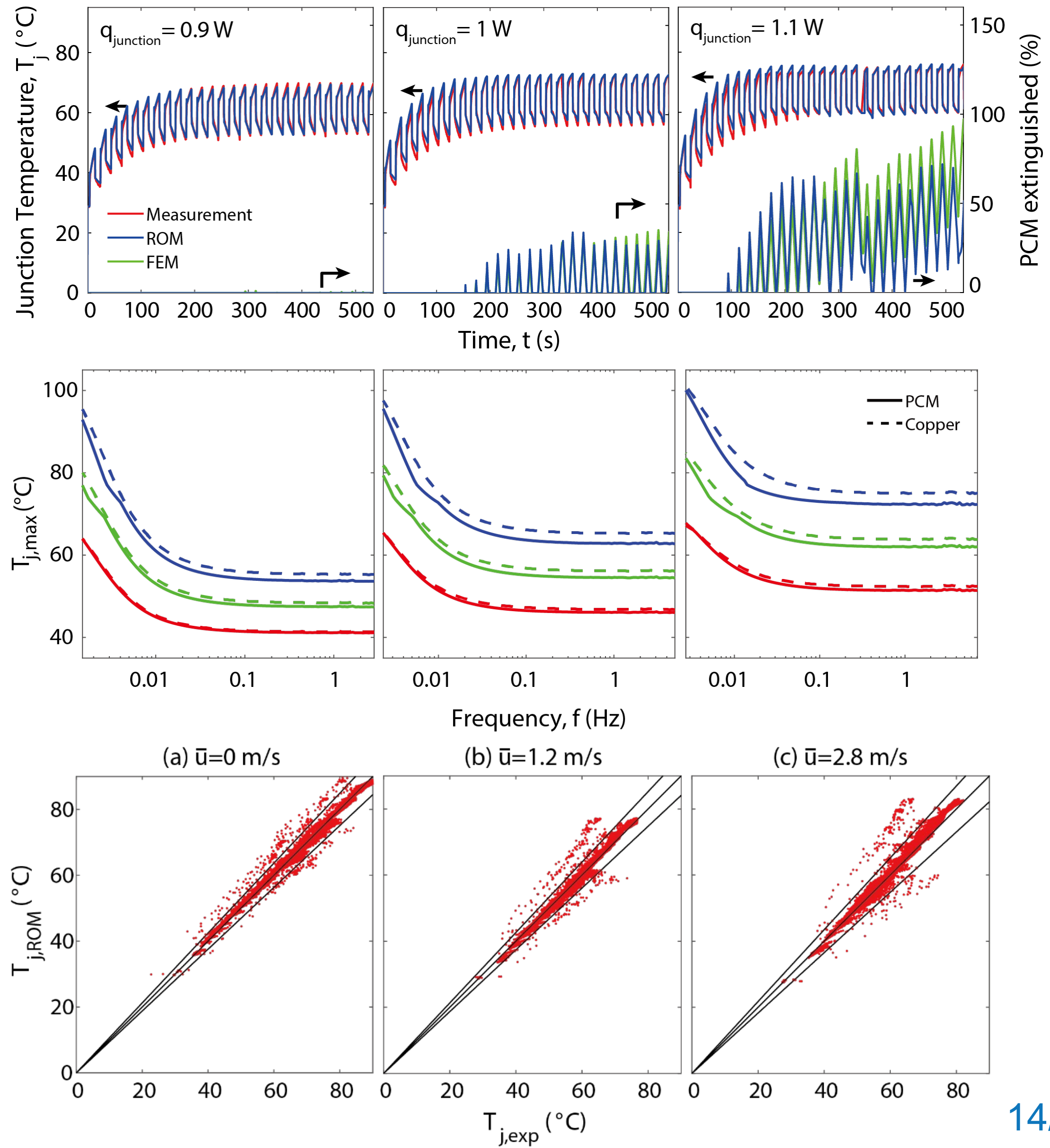
- The relationship between heat absorbed/released is different depending on the phase change status:

  1) Persisting phase change case: Heat absorbed ≈ Heat released

  2) PCM extinguished case: Heat absorbed > Heat released

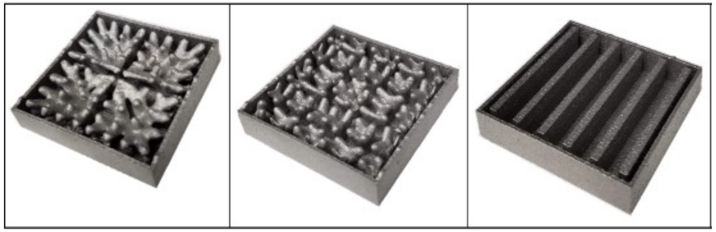


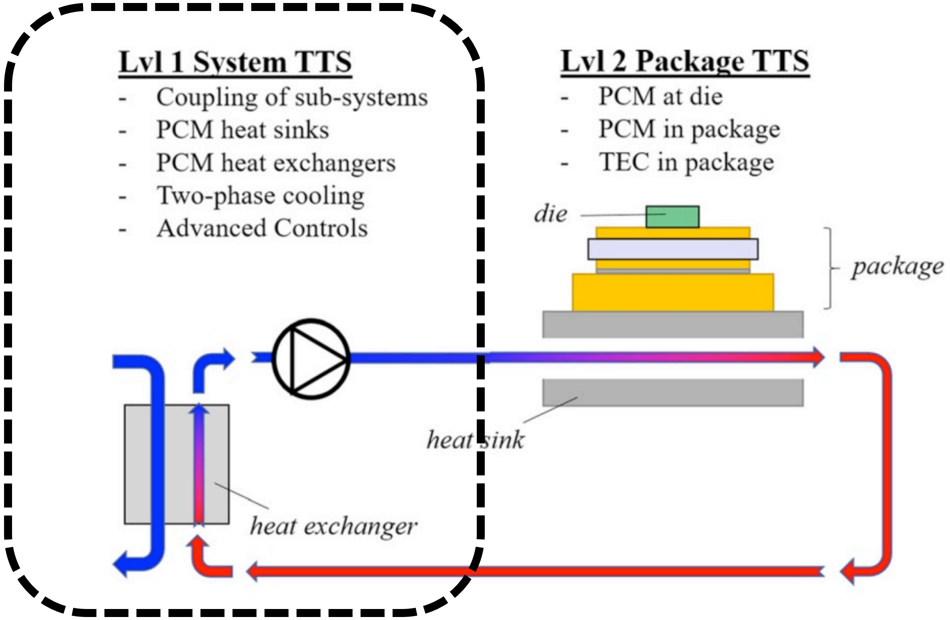
- 1D Resistance-Capacitance (RC) circuit reduced-order model based on lumped capacitance.
- Effective capacitance is varied depending on the PCM temperature.
- 1000X faster estimation when compared to FEM



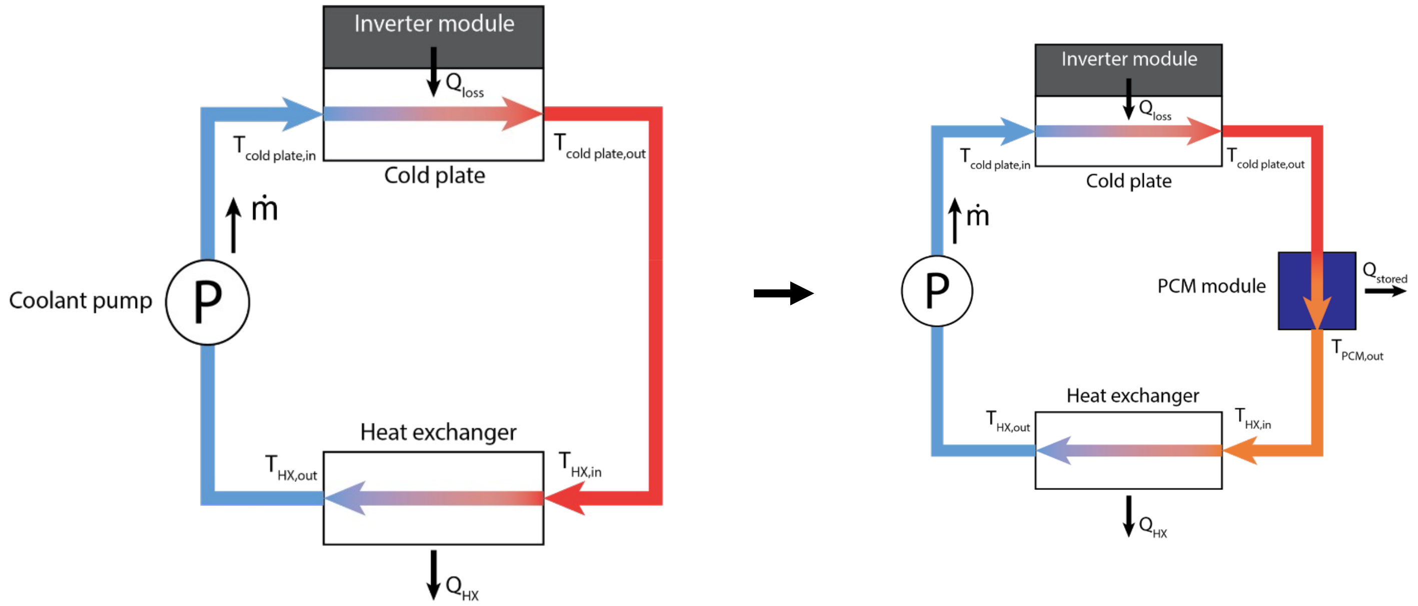
High power density thermal energy storage using additively manufactured heat exchangers and phase change material

Hyunkyu Moon, Tianyu Yang, Nenad Miljkovic, William P. King, David Huitink



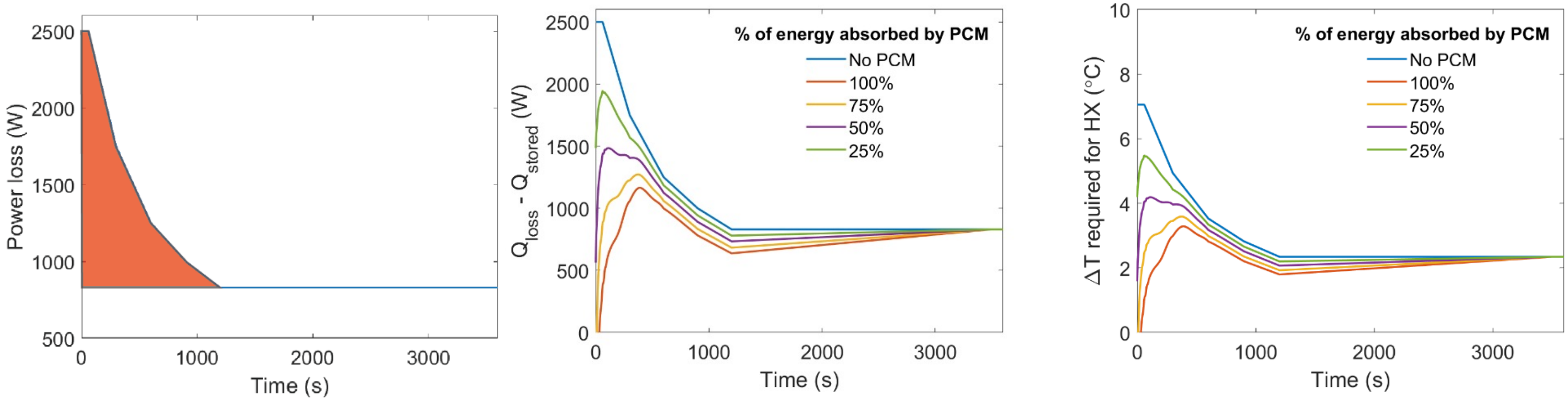


Passive PCM integration Concept



Transient energy in consideration

Passive PCM

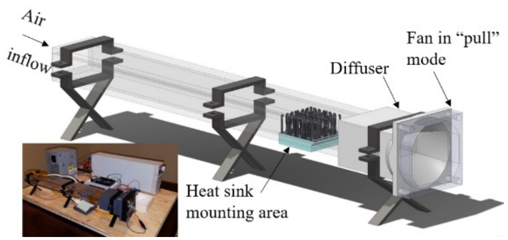


Moon, H., Miljkovic, N., & King, W. P. (2020). High power density thermal energy storage using additively manufactured heat exchangers and phase change material. *International Journal of Heat and Mass Transfer*, *153*, 119591.

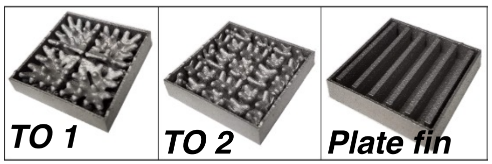
Topology Optimized PCM Heat Sinks

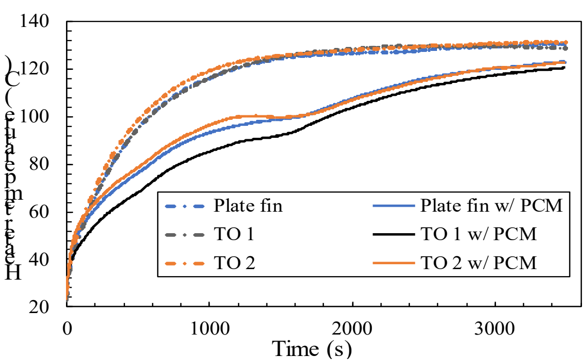
Experiment Methodology

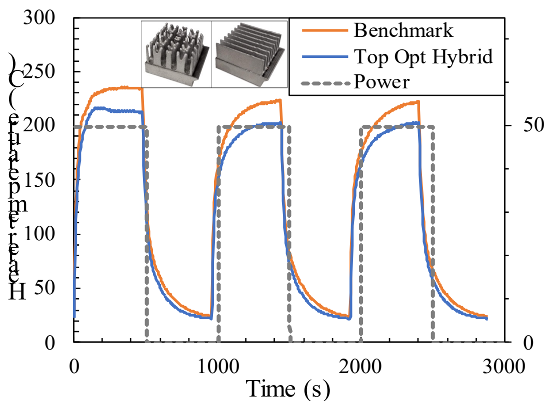
- **Heat sink fin design using a numerical optimization method known as Topology Optimization**
- **Fabrication of the resultant complex fin geometries via additive manufacturing**



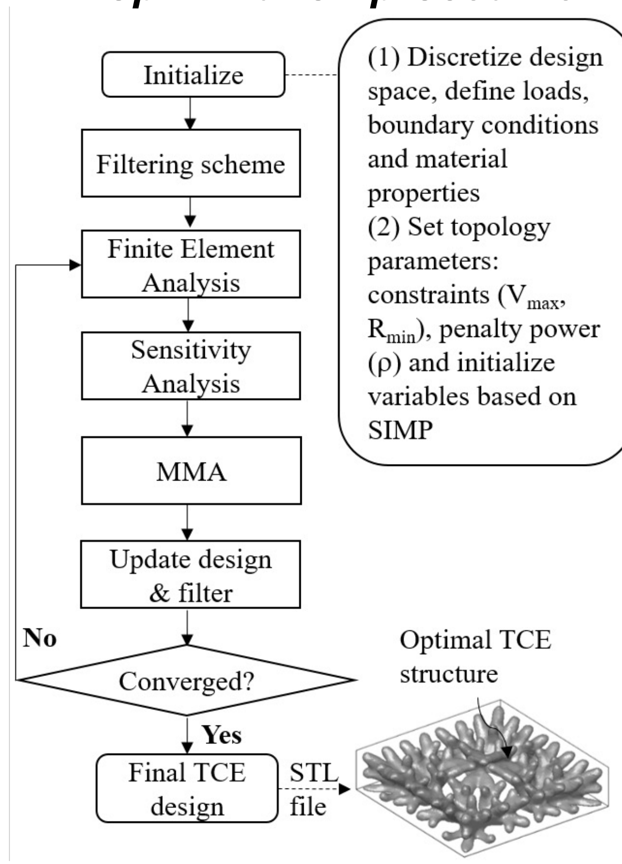
Key Results and Analysis







Flow chart for the topology optimization procedure



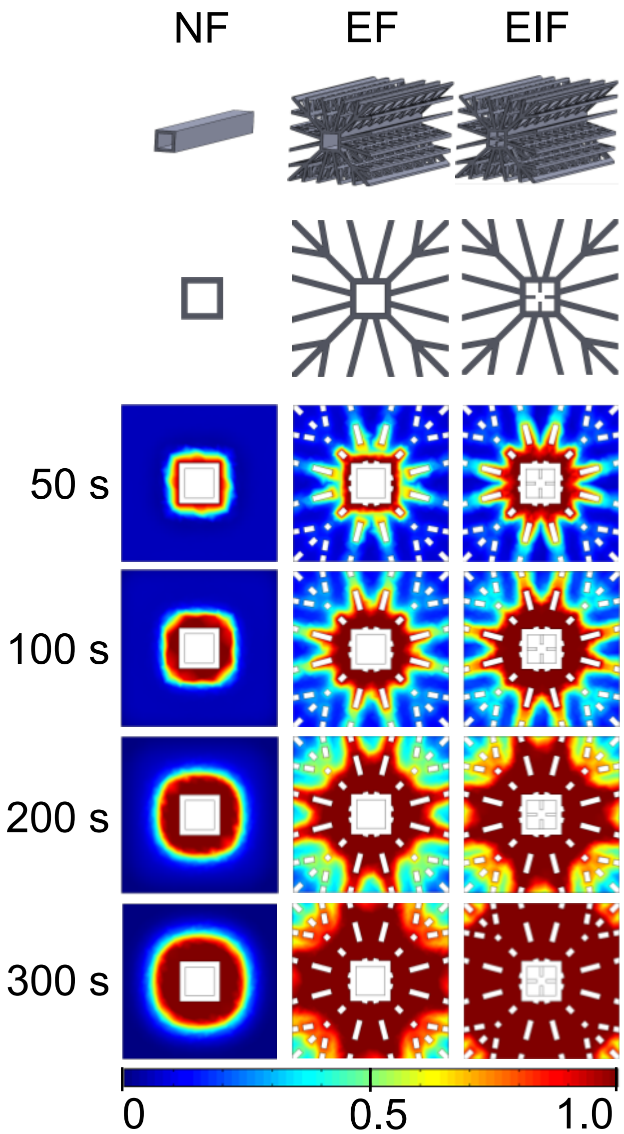
Key Takeaway/Finding/Technology Delivered

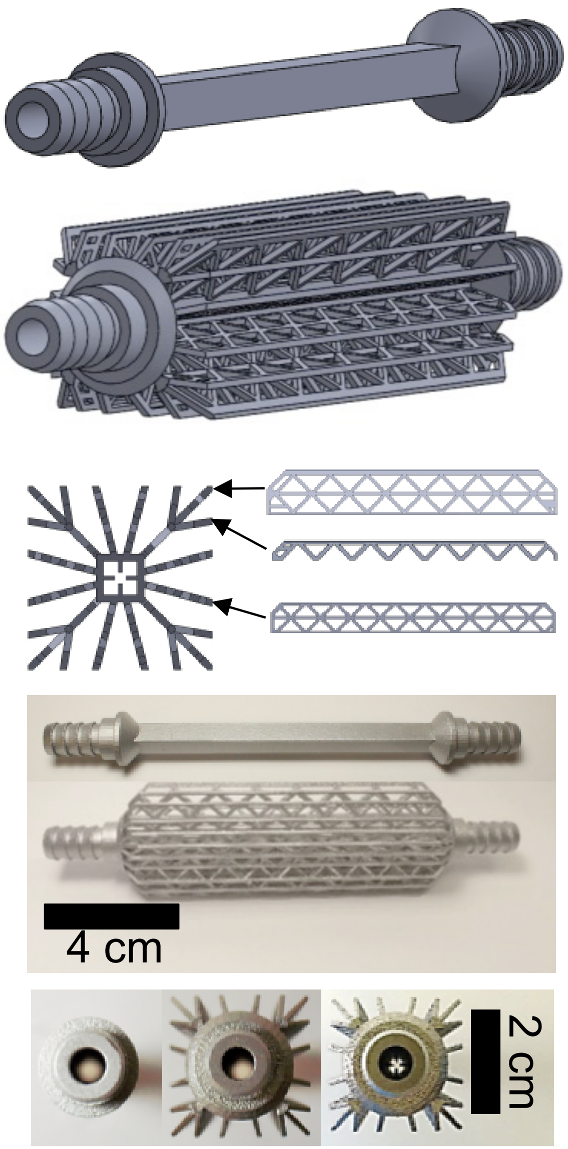
Under a pulsed load of 50 W, the hybrid heat sink lowered peak temp by up to 18.9°C relative to a benchmark plate fin design of similar dimensions

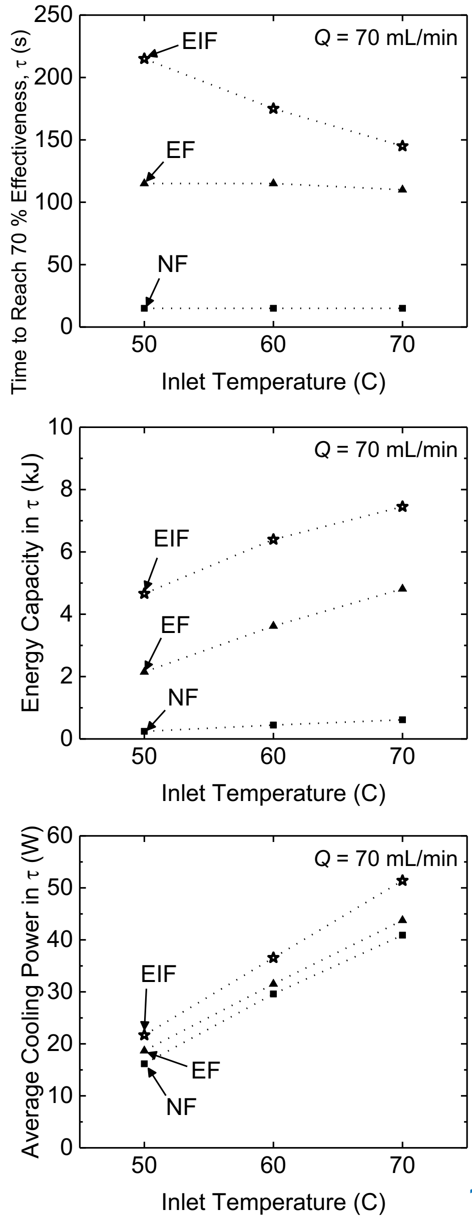
Publications related to this project:
[1] Transient thermal performance using phase change material integrated topology optimized heat sinks, Applied Thermal Engineering, Volume 179,2020
[2] Topology Optimized Phase Change Material Integrated Heat sinks and Validation, ITherm, 2020

Ange-Christian Iradukunda, Andres Vargas, and Danny Lohan

Topology Optimized PCM Heat Sinks





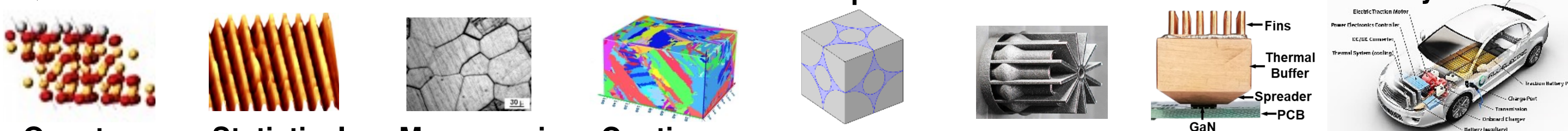


International Journal of Heat and Mass Transfer 153 (2020) 119591

Summary – What is Needed

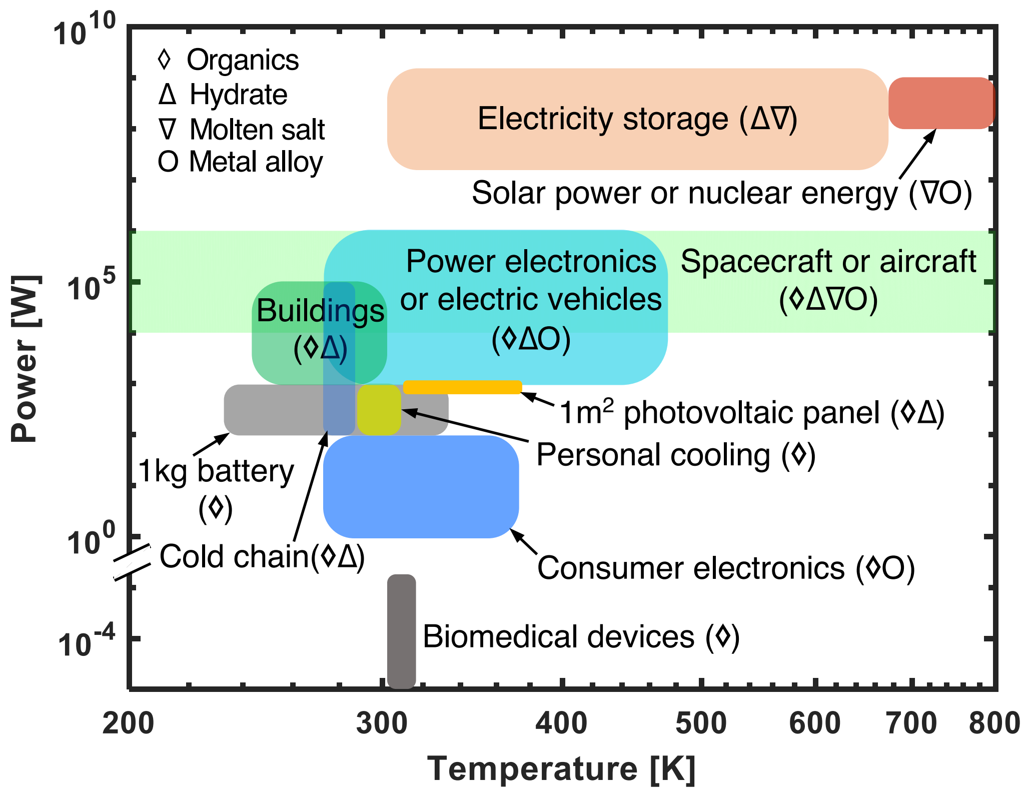
Material design | Device design | Product & system

Scale	Quantum	Atomistic	Mesoscale	Continuum	Composite	Device	Architecture	System
Mechanism	Quantum mechanics	Statistical mechanics	Mesoscopic physics	Continuum mechanics	Effective medium theory	Macroscopic heat transfer	Multiphysics and co-design	
Computation	First principle, DFT, Molecular dynamics, BTE, Monte Carlo, CALPHAD, artificial intelligence				FEM, FVM, FDM, CFD, thermal network modeling, system simulation, artificial intelligence			
Experiment	Optimal synthesis design, Microscopic characterization			Macroscopic measurements			Manufacturing scale-up and automation	



T. Yang, W. P. King, N. Miljkovic, “Phase change material-based thermal energy storage,” *Cell Reports Physical Science*, **2**(8), 100540, 2021.

Questions



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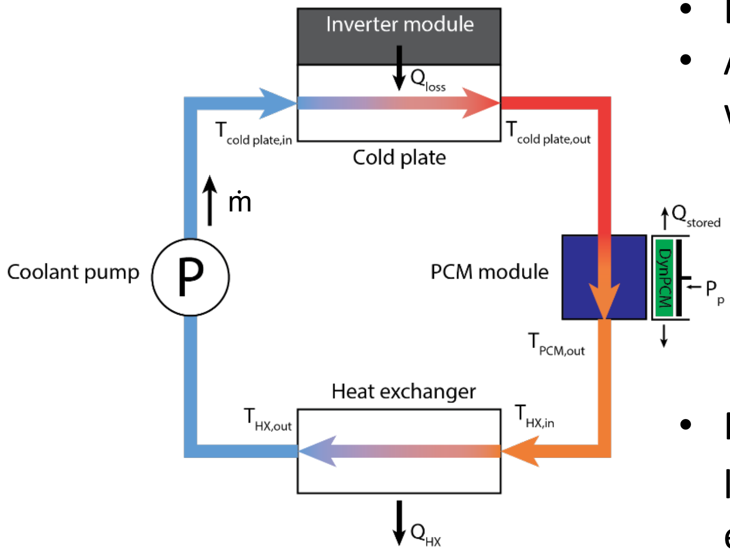
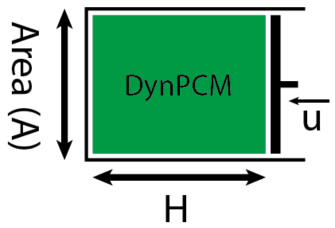
Dynamic PCM integration Concept



- DynParaffin shows q”=5 W/cm^{-2} of cooling capacity
- Assumed appropriate PCM with melting temperature (T_m=70℃) within the operation range (instant phase change from the start)

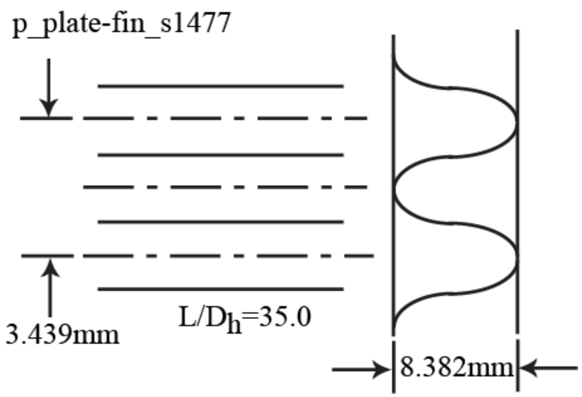


- PCM volume (m^3) & mass (kg) are calculated based on the PCM latent heat (L, kJ/kg), density (ρ_{PCM}, kg/ m^3), and required PCM energy absorption (E_{stored} , kJ)

$$E_{stored} = \int Q_{stored} dt \, , m_{PCM} = \frac{E_{stored}}{L}, V_{PCM} = \frac{m_{PCM}}{\rho_{PCM}}$$

Heat Exchanger

- Surface 14.77



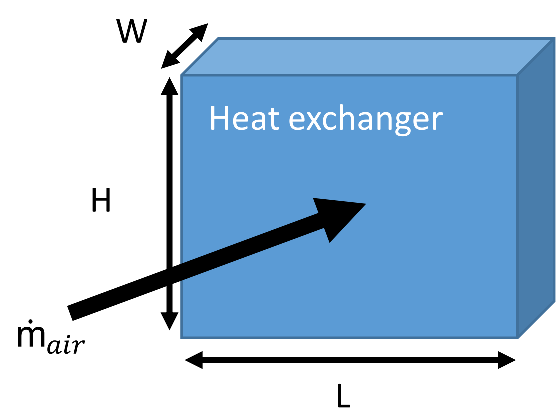
- HX density is assumed to be 500 kg/ m^3
- Coolant is WEG (W 50%, EG 50%,$T_{coolant,in}$=70 °C)
- $\dot{m}_{coolant}$=0.1 kg/s (=6 LPM)
- T_{air}=50 °C
- Assumed h_{air}=50 W/m^{2}K (v_{air}=6.25 m/s) (additional calculation done for h_{air}=25 W/m^{2}K (v_{air}=3.13 m/s))
- For HX sizing, **Length (L) and Height (H) is fixed**, and **Widt h (W) is varied**

Air side characteristics (tabulated)

Fin pitch, p	582/m
Hydraulic dia, 4 r_h	2.59E-03 m
Metal thickness, δ	1.52E-04 m
Free flow area / frontal area, σ	0.7
HT area / vol of HX, α	1358 m^2/m3
Fin area / Total area	0.844

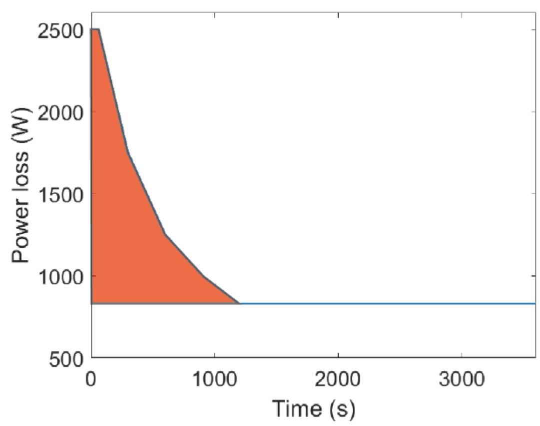
Water side characteristics (calculated)

Frontal area/tube	2.90E-04 m^2
Flow area/tube	6.32E-05 m^2
Perimeter of tube (per length)	5.49E-02 m
flow/frontal	0.218
HT area/vol	188.98 m^2/m^3
Hydraulic diameter, 4 r_h	4.60E-03 m

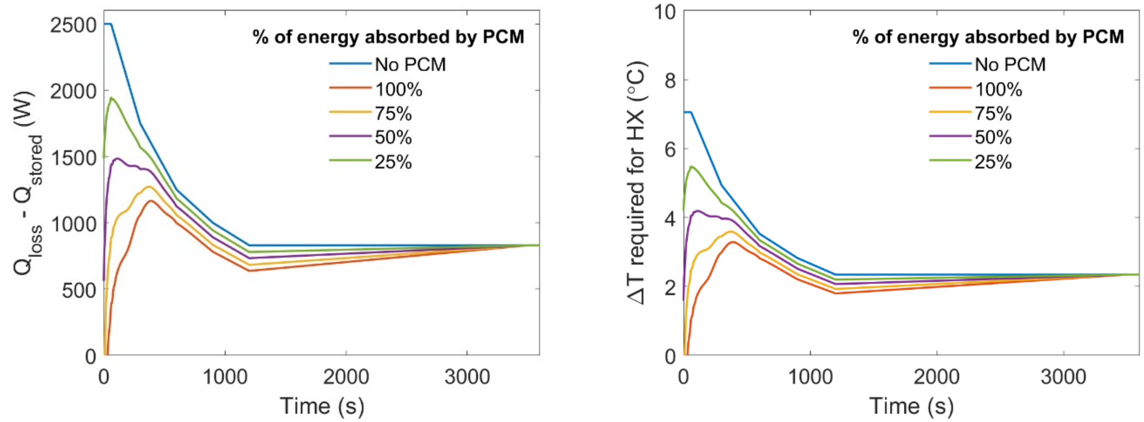


Calculations

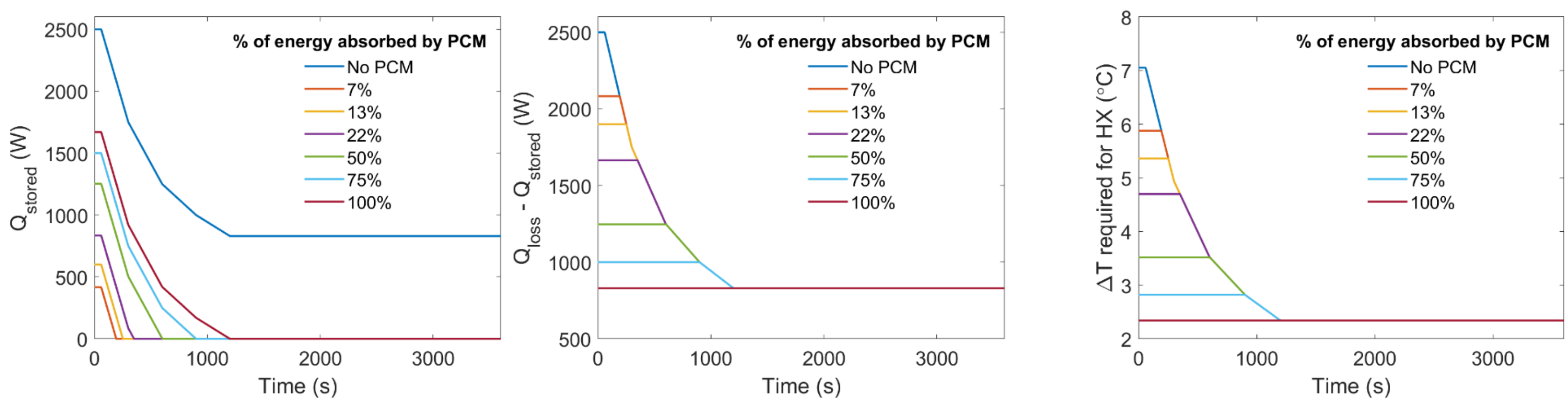
Transient energy in consideration



Passive PCM

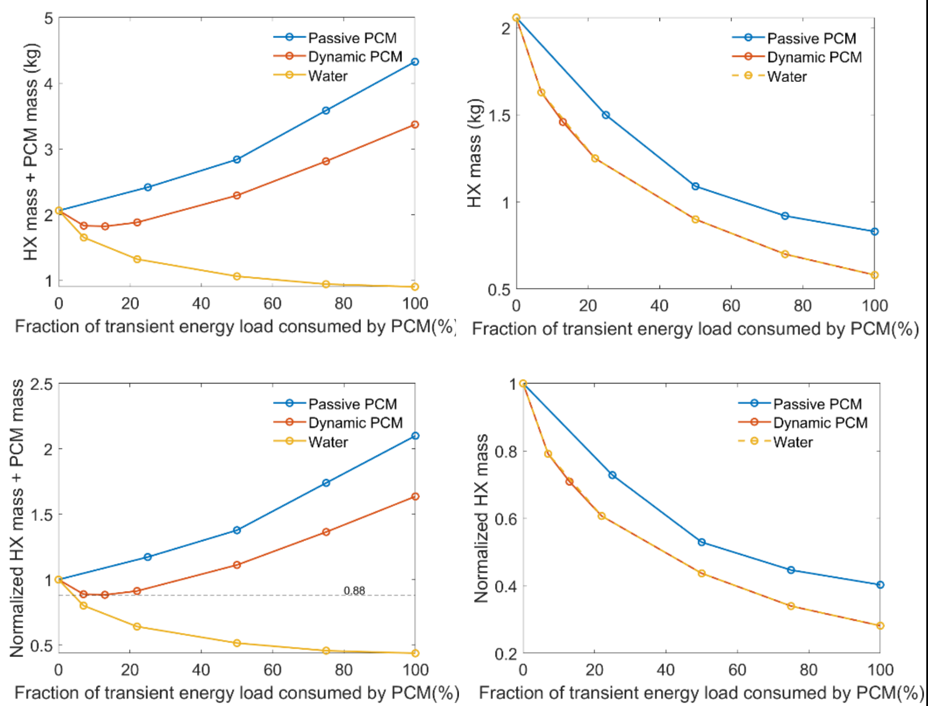


Dynamic PCM

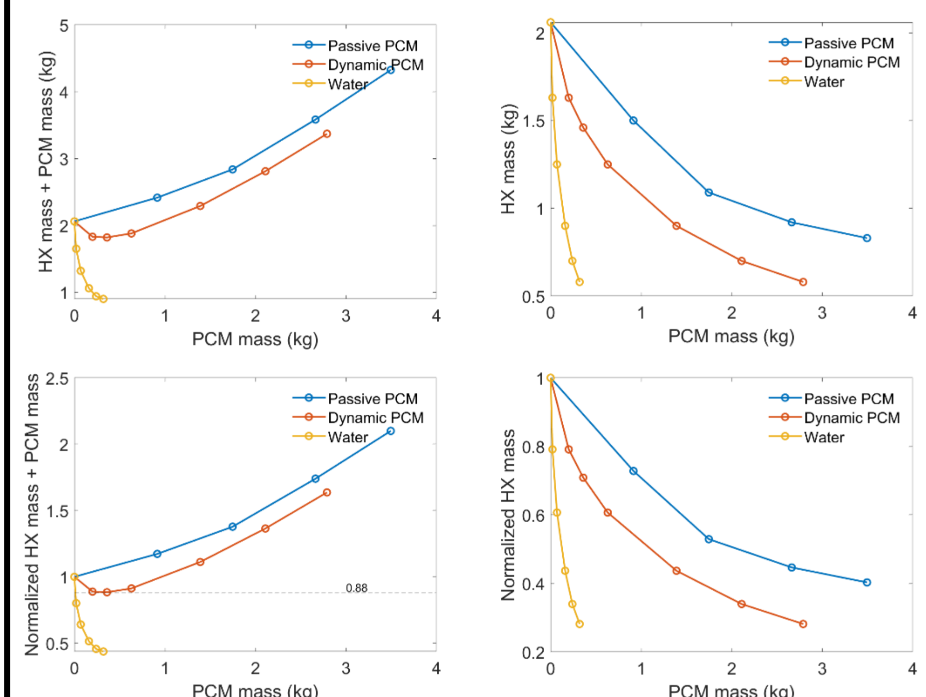


Calculations(h_{air}=50 W/m^2K)

vs Fraction of total transient energy



vs PCM mass



Dynamic Phase Change Material Using Pressure-enhanced Close Contact Melting

Wuchen Fu, Xiao Yan, Yashraj Gurumukhi, Vivek S. Garimella, William P. King, and Nenad Miljkovic

University of Illinois, Urbana-Champaign

Conclusions

1. DynPCMs can stabilize surface temperature - thermal management applications.

2. The heat transfer rate can be enhanced by 10X by forming a micro-scale thin liquid layer - thermal storage applications.

3. A robust and controllable relationship exists between the applied heat flux, applied pressure and stabilized surface temperature. A model has been established and validated.

More details can be found in:
Fu, W., Yan, X., Gurumukhi, Y., Garimella, V.S., King, W.P. and Miljkovic, N., 2022. ***High power and energy density dynamic phase change materials using pressure-enhanced close contact melting****. Nature Energy, 7(3), pp.270-280.*

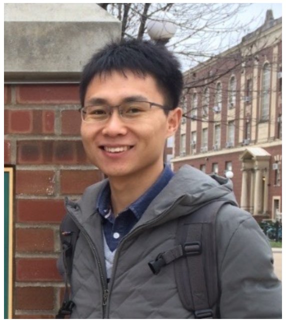
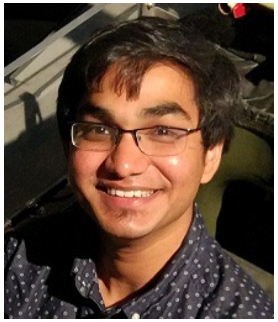





Figure S1

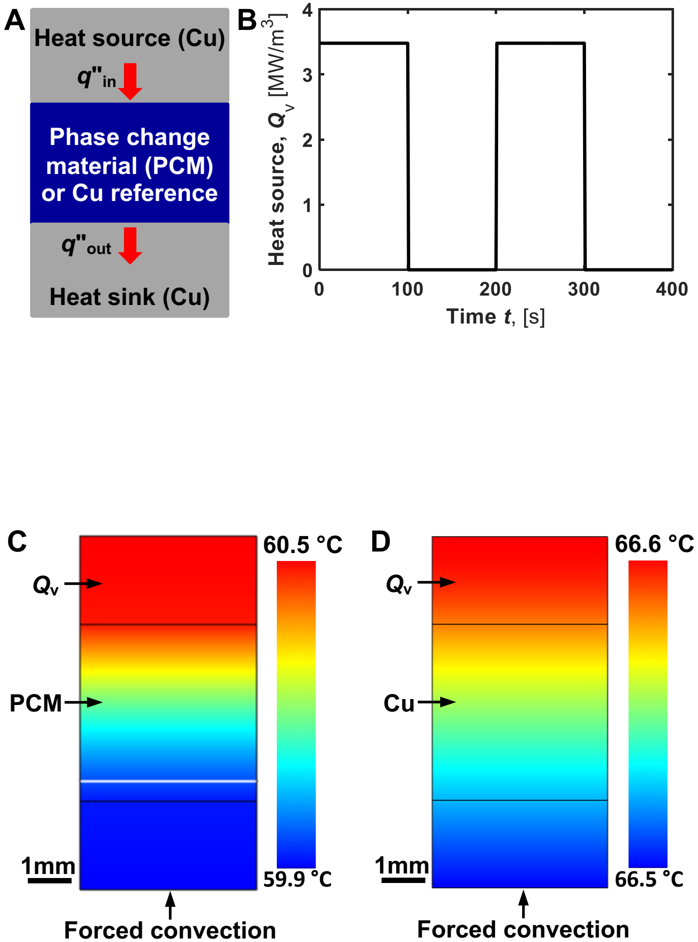

A
Heast source (Cu)
q"in
Phase change material (PCM) or Cu reference
q"out
Heat sink (Cu)
B
Heat source, Qv [MW/m3]
Time t, [s]
0
1
2
3
4
100
200
300
400
C
Qv
PCM
1mm
60.5 °C
59.9 °C
Forced convection
D
Qv
Cu
1mm
66.6 °C
66.5 °C
Forced convection

Table S1

PCM type	Organics	Hydrate	Molten salt	Metal alloy
Corrosivity [g/($m^2 \cdot d$)]	0-2	0-20	0-30	0-5
Supercooling [K]	0-5 (10-60 for alcohols)	10-30	10-20	5-100
Durability	Decomposition and flammability	Phase separation	Volatility in liquid	Oxidation
Cost [$/kWh]	20-100	1-20	1-30	20-200
Cost [k$/ton]	1-10	0.1-2	0.2-3	1-20

Background

Phase change material (PCM)


Paraffin


Ice

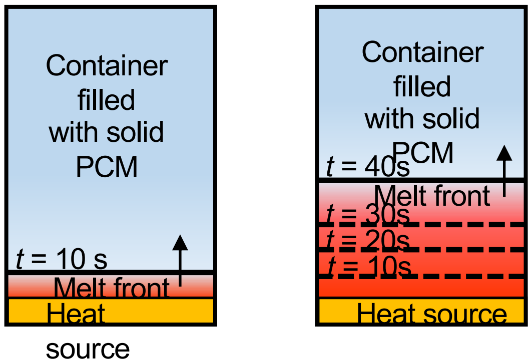
Intrinsic high latent heat: > 200 kJ/kg
Passively absorb/release heat
Cost effective, paraffin wax ~$500/ton

Commercial Ice Energy Storage (Calmac, Trane):

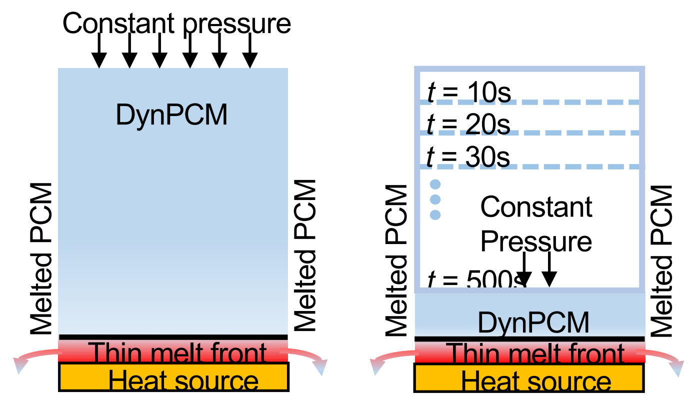
Source: http://www.calmac.com/icebank-energy-storage-model-c

Opportunities:
Thermal management and thermal energy storage

Challenges:
Low thermal conductivity => low heat transfer rate => low power density

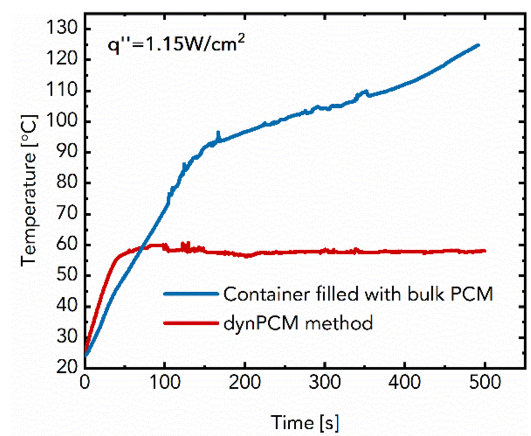


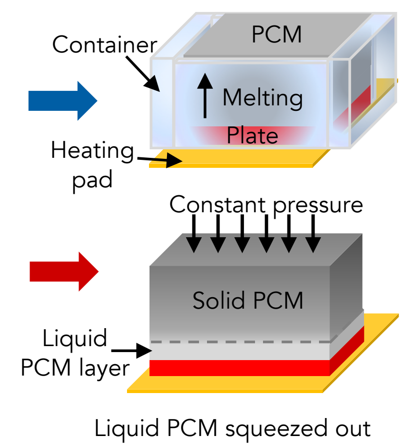
Conventional PCM Method

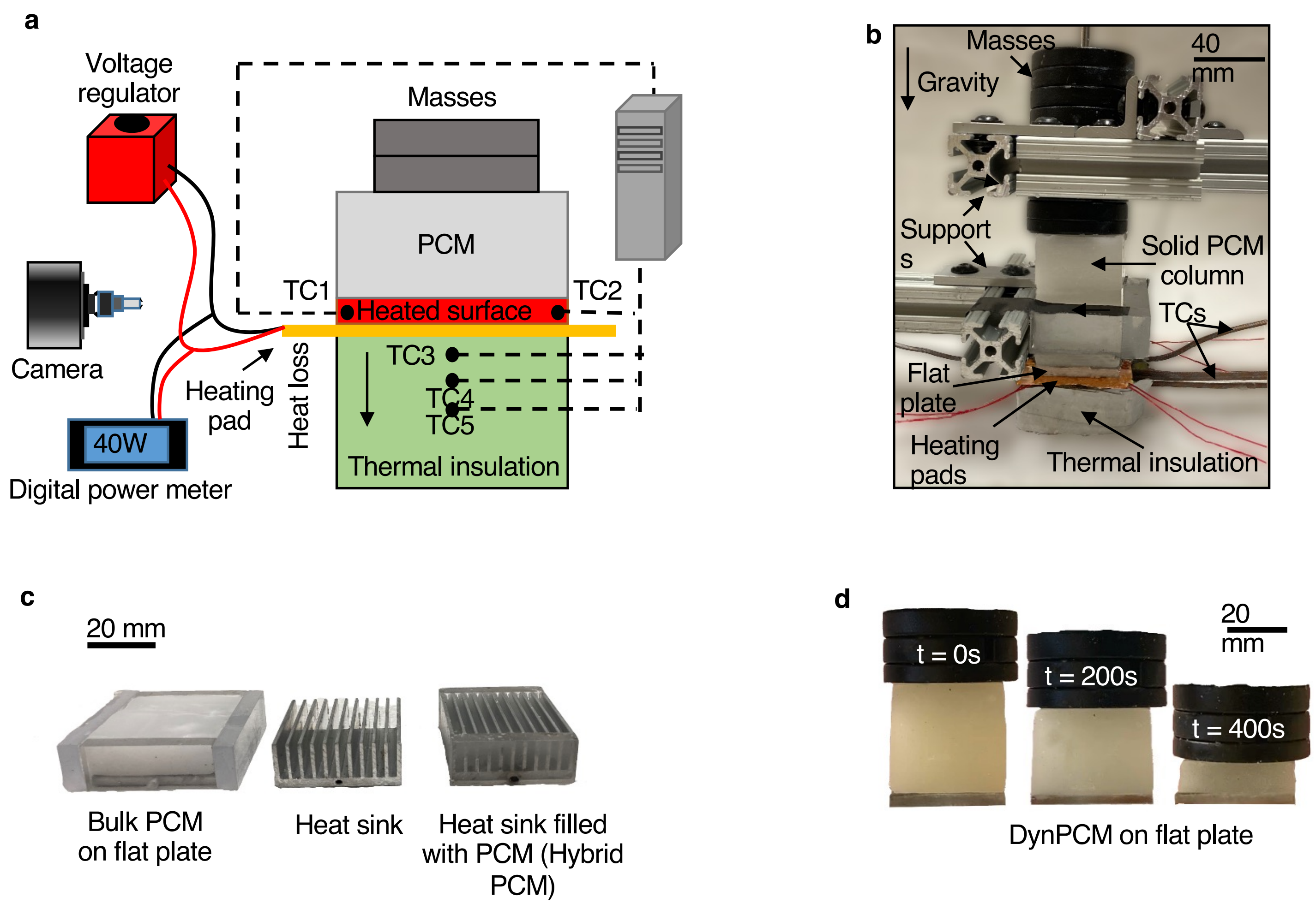


Dynamic PCM Method

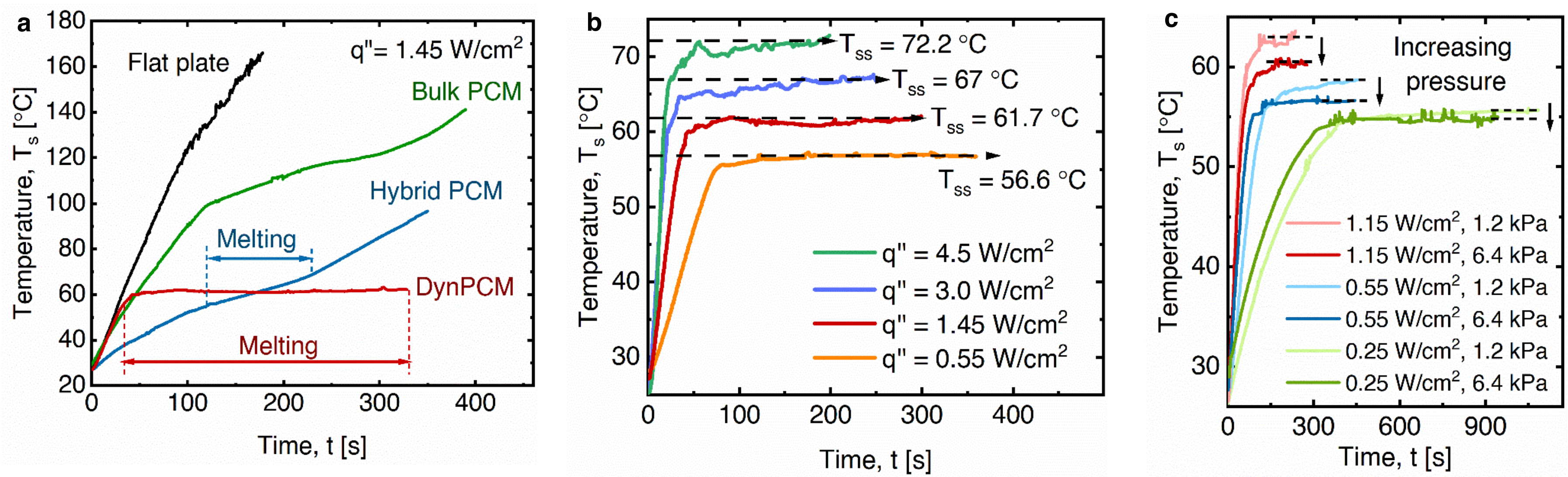
- **Conventional method:** PCM reduces the temperature increase rate, but the heat source temperature still increases.
- **DynPCM method:** surface temperature is stabilized via the formation of a robust thin melt liquid layer.





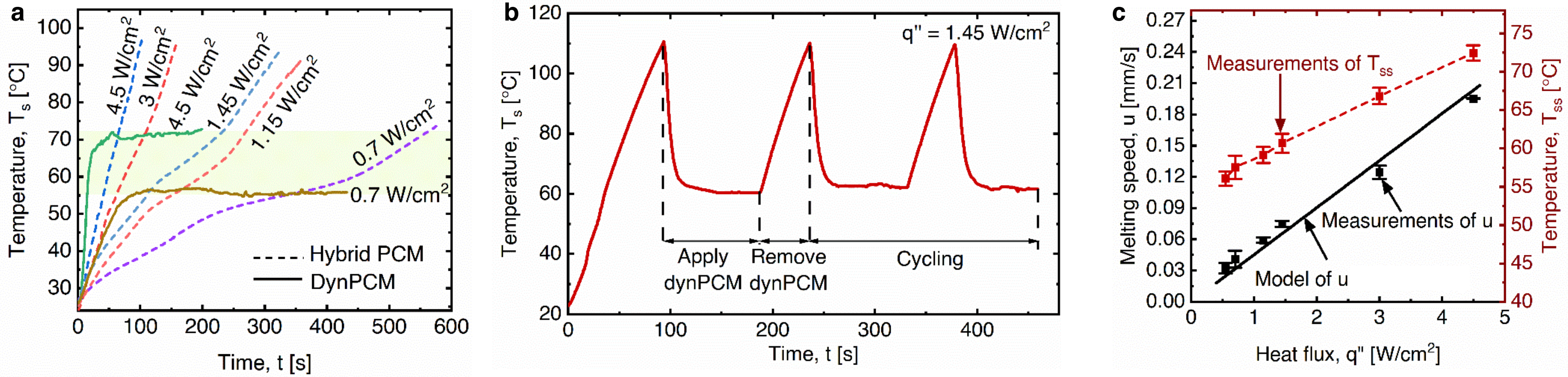

a
Voltage regulator
Masses
PCM
TC1
TC2
Heated surface
Camera
Heating pad
Heat loss
TC3
TC4
TC5
40W
Thermal insulation
Digital power meter
b
Masses
40 mm
Gravity
Supports
Solid PCM column
TCs
Flat plate
Heating pads
Thermal insulation
c
20 mm
Bulk PCM on flat plate
Heat sink
Heat sink filled with PCM (Hybrid PCM)
d
t = 0s
t = 200s
t = 400s
20 mm
DynPCM on flat plate

Experimental Results



q”: Applied constant heat flux
T_s: Heater surface temperature
T_{ss}: Steady state surface temperature (for DynPCM)
P: Applied pressure (6.4 kPa if not mentioned).

- All DynPCM cases stabilized once the temperature arrived at its stead state temperature (T_{ss}).
- At same applied pressure (P), higher heat fluxes result in higher T_{ss}.
- At same heat flux (q”), higher pressures results in lower T_{ss}.
- A robust relationship (model) exists to link T_{ss}, P, and q”.



Heat sink filled with PCM (Hybrid PCM)

- Surface temperature always converges to the same constant temperature - dynPCM is a robust steady state process.

$$u = \frac{q''}{\rho_s L + (T_m - T_i)\rho_s C_{p,s}}$$

- **Assumptions of model for *u***:
- All energy absorbed by the PCM.
- Neglect sensible heat absorbed by superheated liquid (melt PCM).

Liquid layer thickness (Stefan adhesion):

$$\delta_R = \sqrt[3]{\frac{3R^2\mu_l u}{2P}}$$

Fourier's law (1-D):

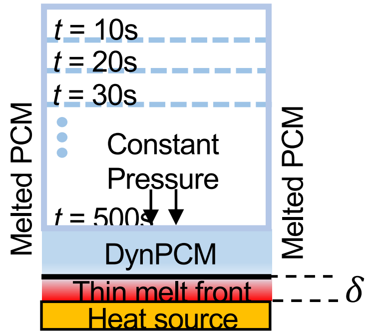
$$q'' = k_l \frac{T_{ss} - T_m}{\delta}$$

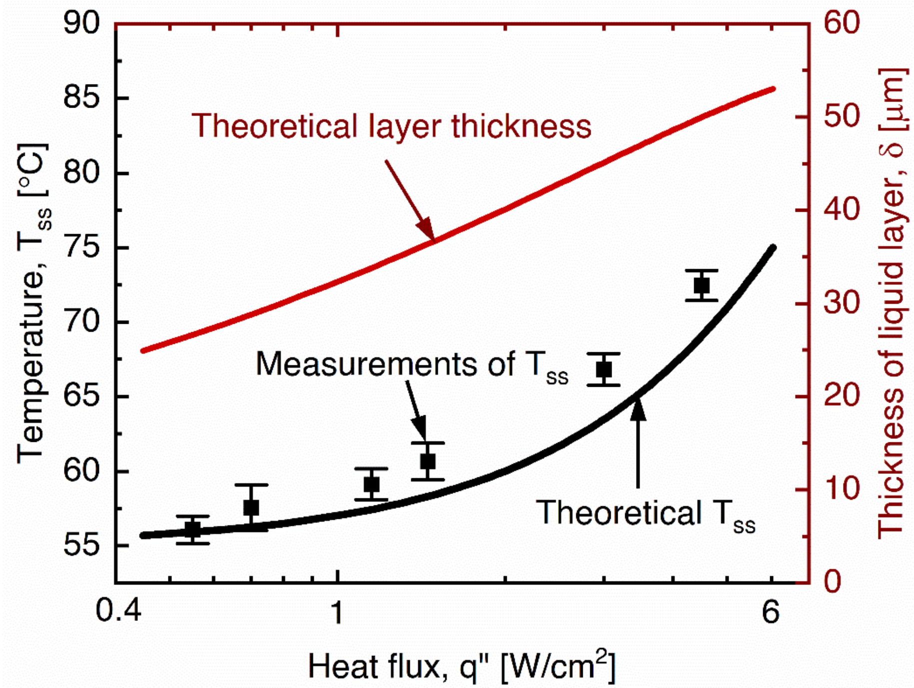
Dropping speed:

$$u = \frac{q''}{\rho_s L + (T_m - T_i)\rho_s C_{p,s}}$$

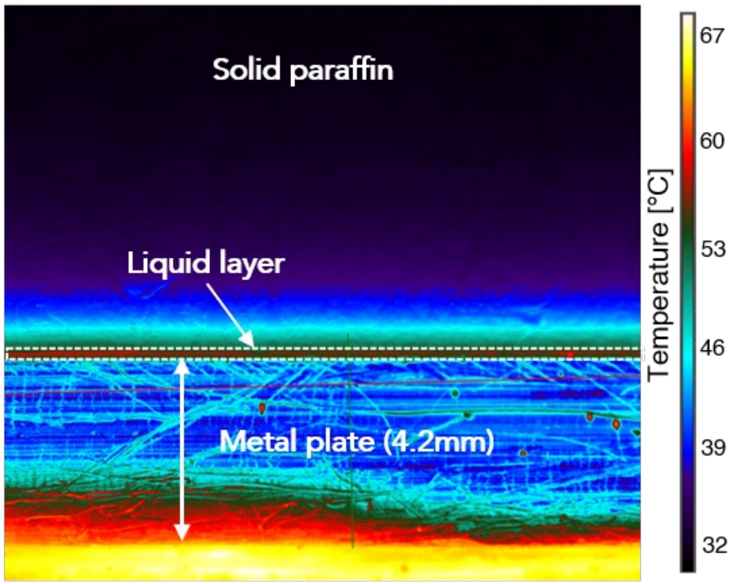
Our model (Theoretical T_{ss} - black curve):

$$T_{ss} = T_m + 0.75 k_l^{-1} (q'')^{\frac{4}{3}} \left[\frac{\rho_s\big(L + (T_m - T_i)C_{p,s}\big)P}{W^2 \mu_l}\right]^{-\frac{1}{3}}$$

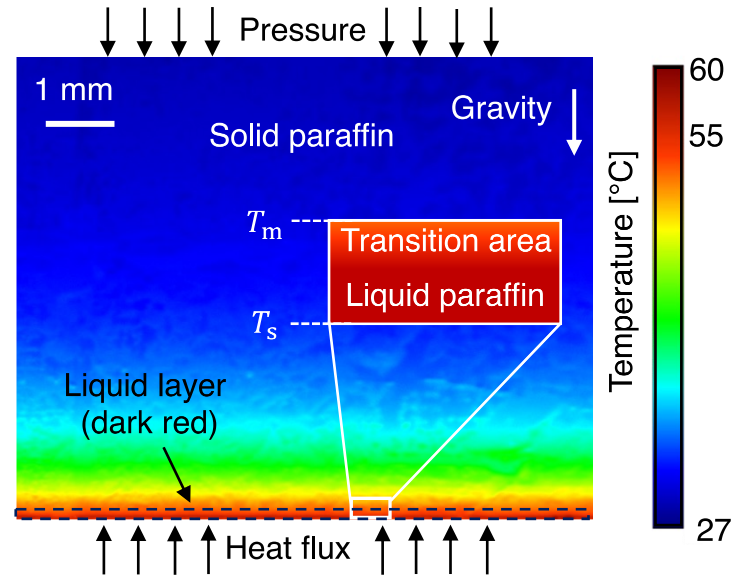




Model and Validation – Infrared Imaging



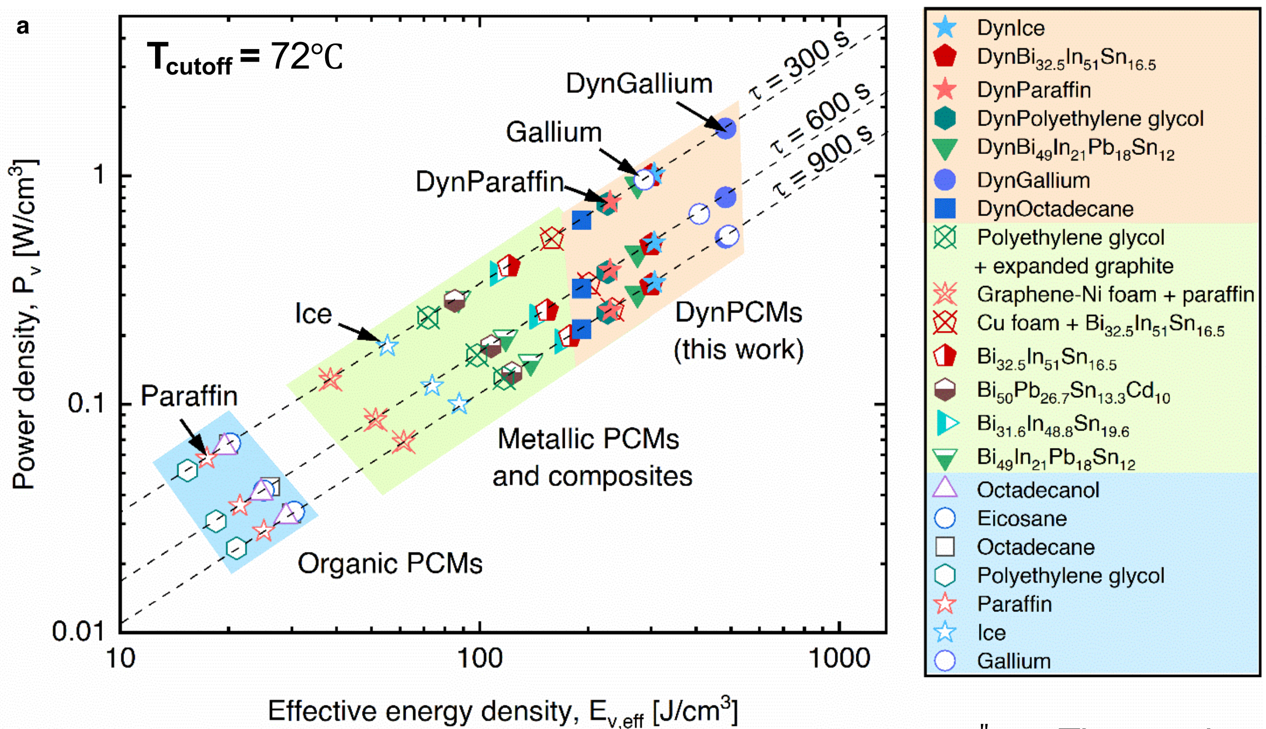
Original IR Image

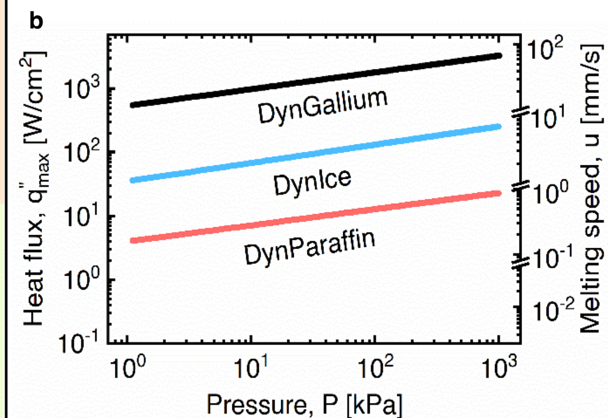


Higher Magnification IR Image

Measured layer thickness：52 µm ± 13 µm
Theoretical layer thickness：~40 µm

Energy and Power Density





τ: Effective cooling time: 300/600/900s

$$P_v = \frac{q''_{max}}{H} \qquad E_{v,eff} = \frac{q''_{max} A\tau}{AH} = P_v \tau$$

q''_{max}: The maximum heat flux can be applied to the surface, so that the surface temperature will not exceed $\mathbf{T_{cutoff}}$ in τ seconds