Marconnet Thermal
& Energy Conversion Lab

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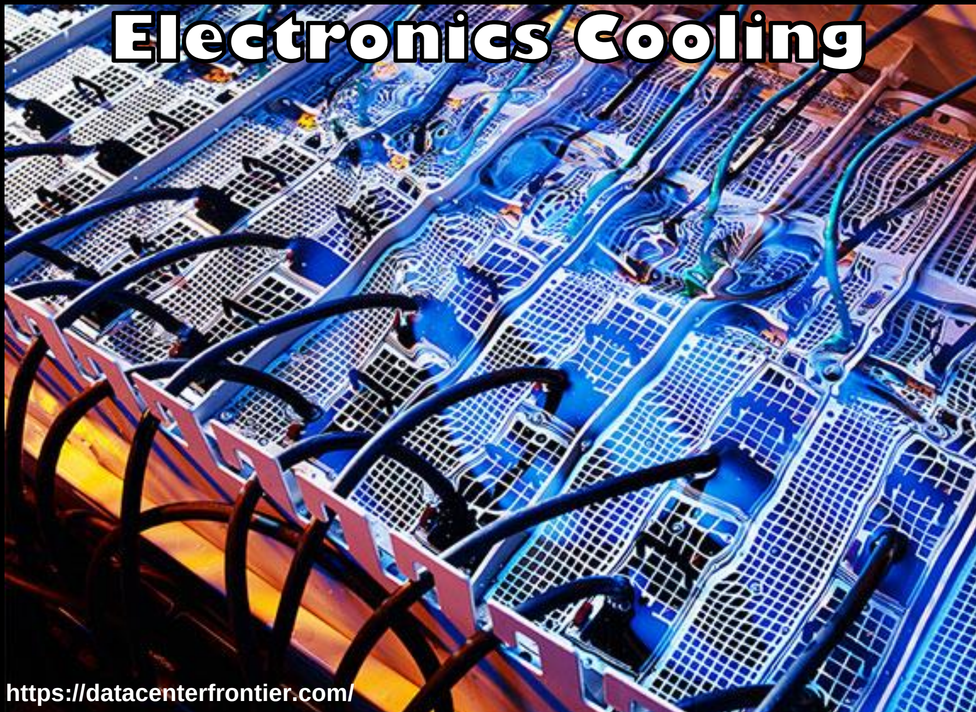
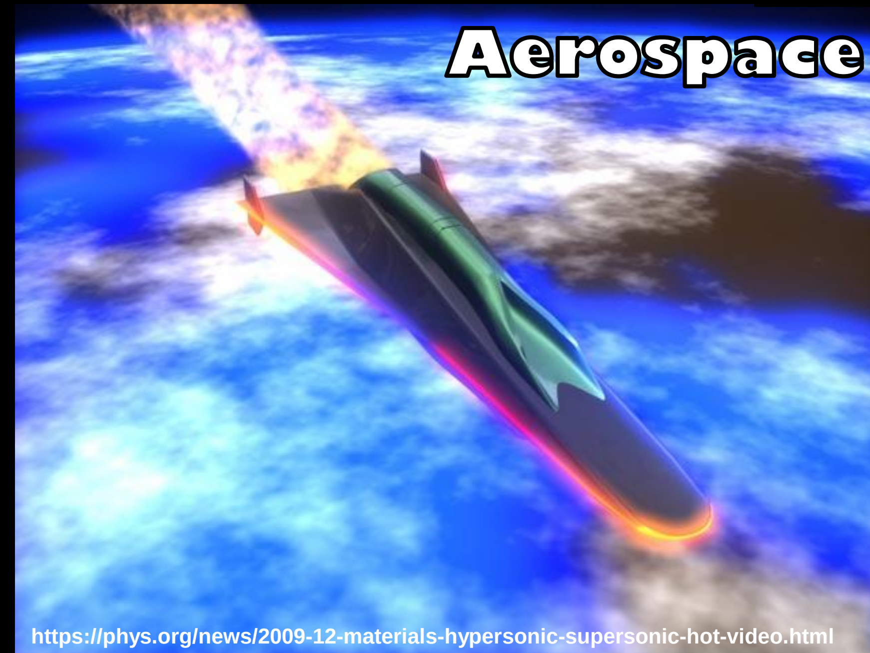
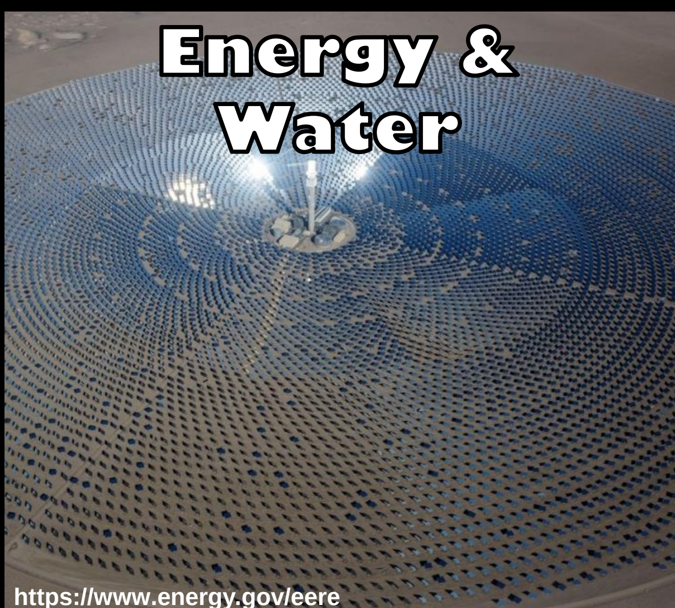
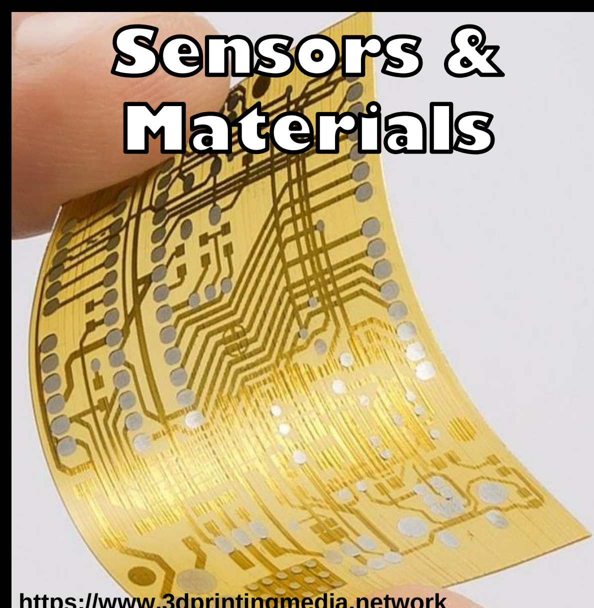

Electronics Cooling
https://datacenterfrontier.com/

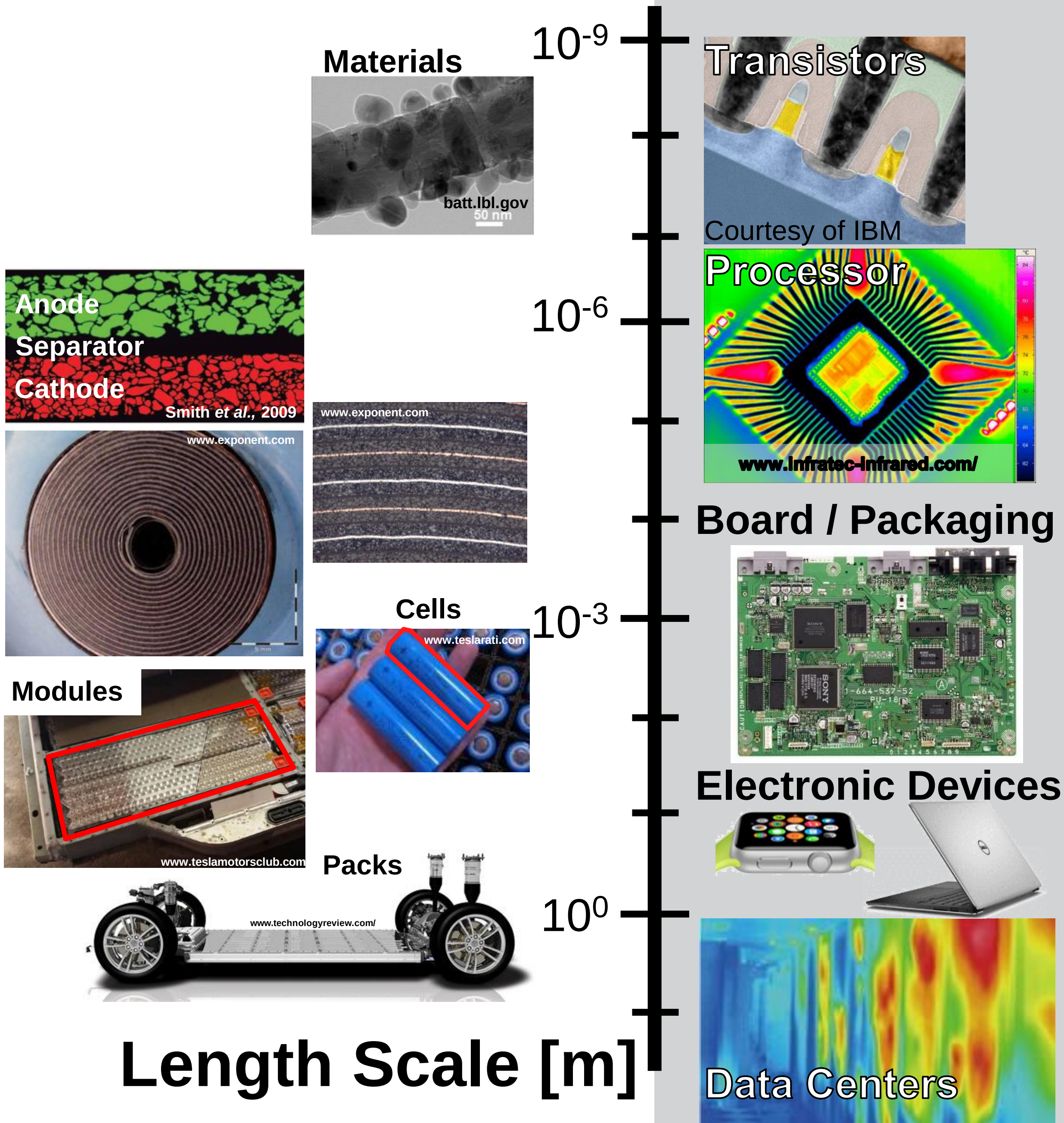

Aerospace
https://phys.org/news/2009-12-materials-hypersonic-supersonic-hot-video.html


Energy &
Water
https://www.energy.gov/eere


Sensors &
Materials
https://www.3dprintingmedia.network


Batteries
https://greentransportation.info/
ev-ownership/safer/tesla-model-s-2013.html

Heterogeneous & Multi-Scale Systems



Metrology Development & Property Analysis

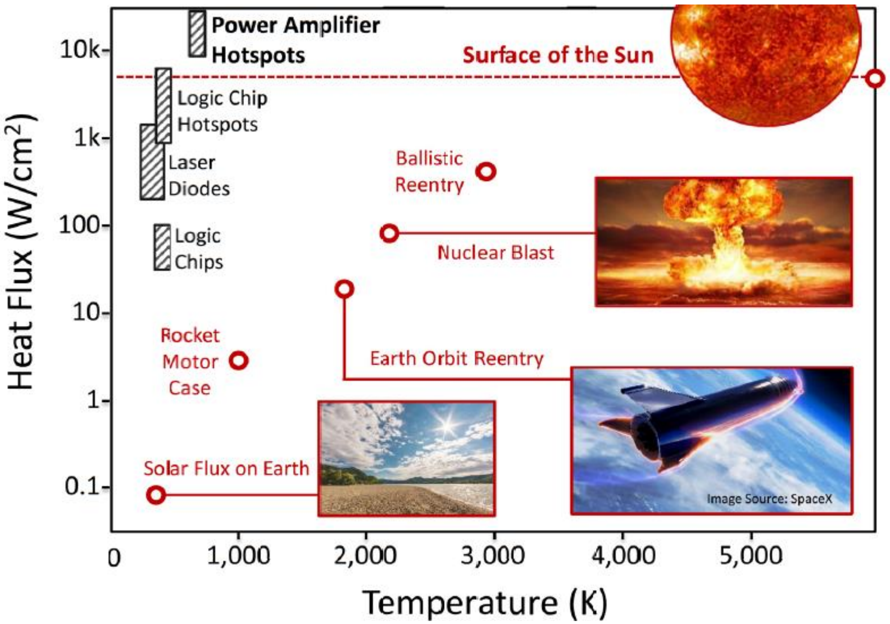
Thermal Management Solution Development

Fundamental Transport Phenomena Analysis

Thermal Challenges for (High Powered) Electronics

Increasing Heat Fluxes Demand New Cooling Solutions

Weibel (2020), ME 511 Lecture Notes

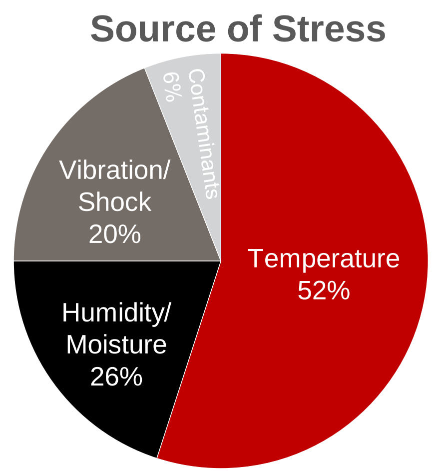


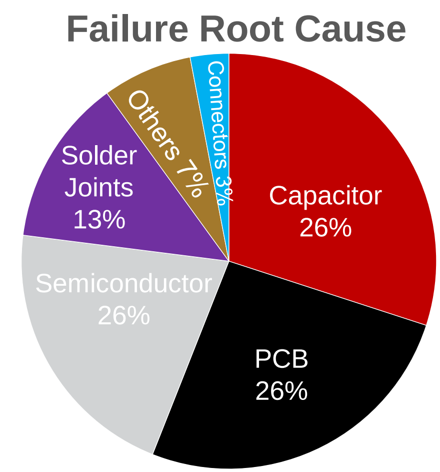
Move the Heat → Enhanced Conduction in Materials & Interface

Store the Heat → Passive Thermal Management w/ PCMs

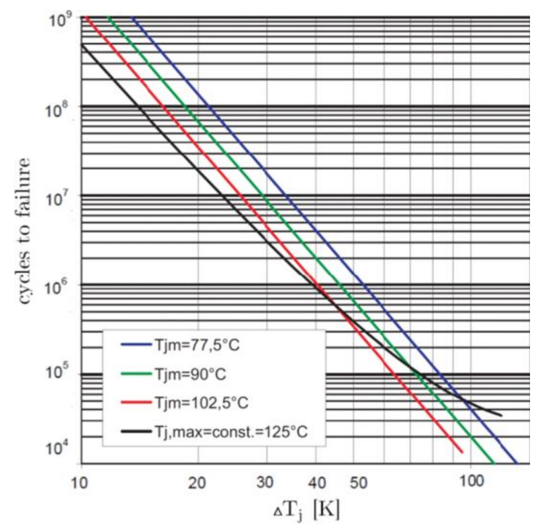
Control the Heat → Thermal Switches

Temperature Drives Significant Portion of Failures in Power Electronic Devices





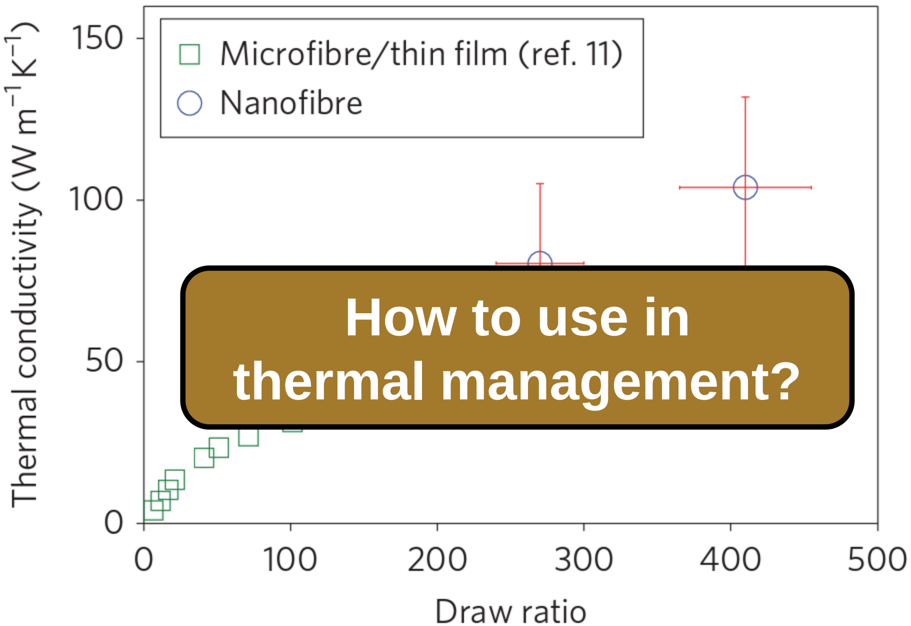
Wang *et al.*, *IEEE Industrial Electronics Magazine*, 2017



Andersen *et al.*, *IEEE Transactions on Power Electronics*, 2017.

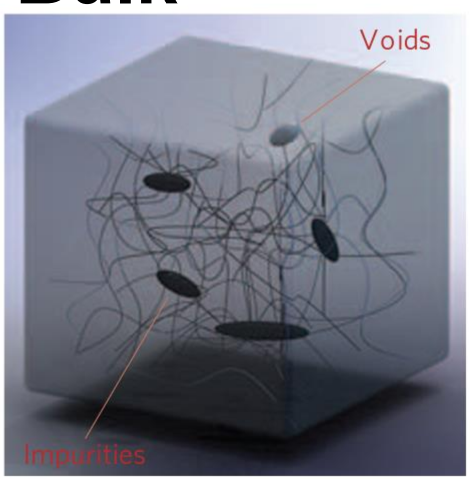
High Thermal Conductivity Polymers

Alignment of polymer chains can lead to ultrahigh thermal conductivities



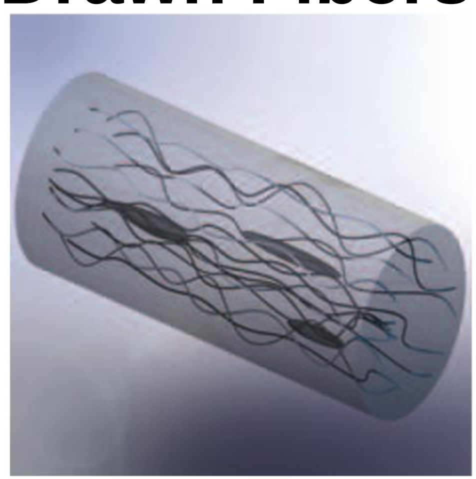
How to use in thermal management?

Bulk



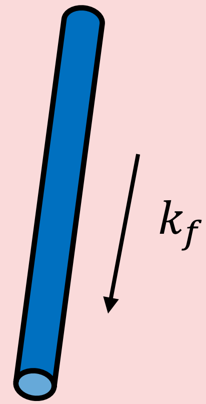
Drawn Fibers

c



S. Shen, A. Henry, J. Tong, R. Zheng, and G. Chen, *Nature Nanotechnology: Letters*, 2010.

Our Work



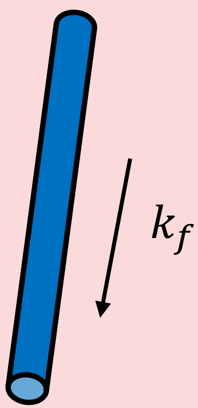
Dyneema Fiber thermal conductivity

25-30 W/mK

A.A. Candadai, J. A. Weibel, and A. M. Marconnet, *ACS Appl. Polym. Mater.* 2020

Thermal Conductivity: From Fibers to Fabrics

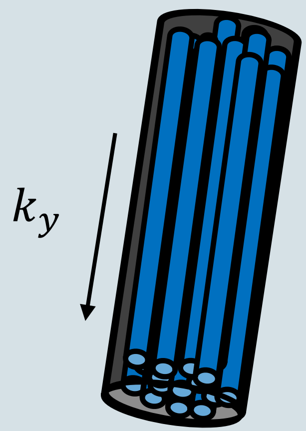
Fibers



✓ Fiber thermal conductivity

25-30 W/mK

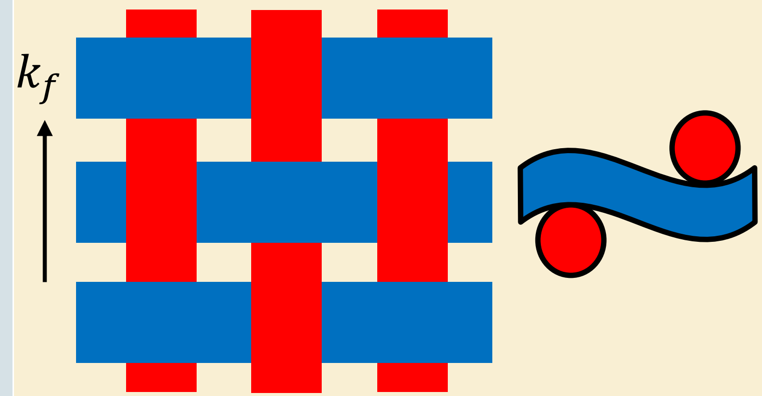
Yarns



✓ Yarn thermal conductivity

16-18 W/mK

Fabrics



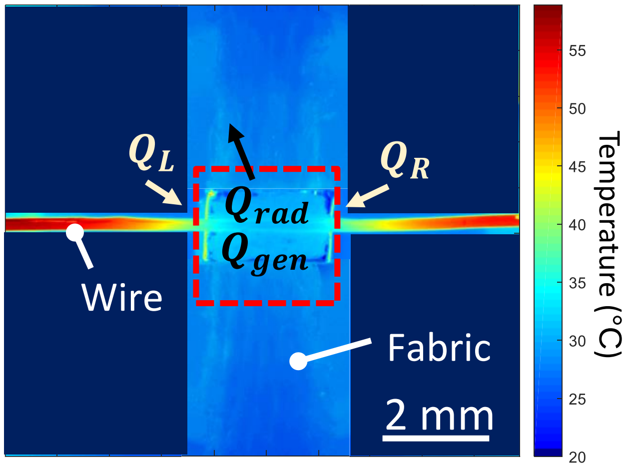
✓ Fabric thermal conductivity (in-plane high density direction)

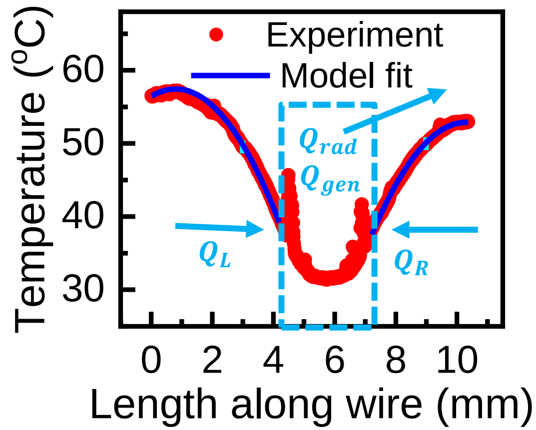
9-10 W/mK

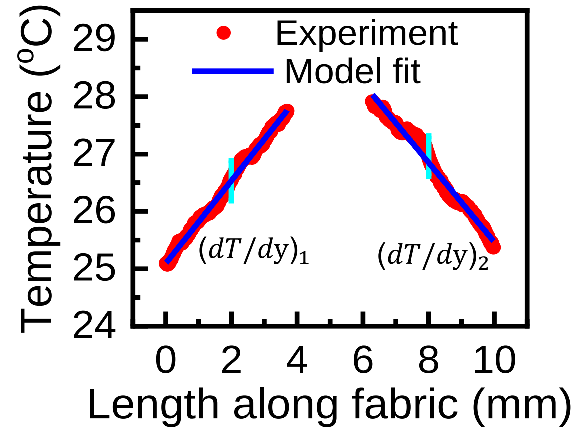
→ Effective thermal conductivity reduces

A.A. Candadai, J. A. Weibel, and A. M. Marconnet, *ACS Appl. Polym. Mater.* 2020

New Thermal Metrology Technique



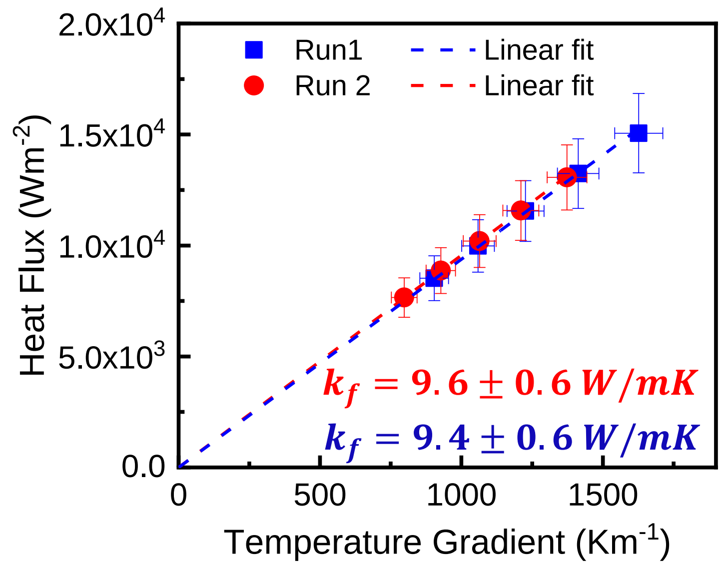




$$k_f = \frac{Q_L + Q_R + Q_{gen} - Q_{rad}}{A*((dT/dy)_1 + (dT/dy)_2)}$$

Rectangular cross-section is assumed for area calculation (effective width and thickness measured)

Fabric thermal conductivity = 9-10 W/mK



A.A. Candadai, J. A. Weibel, and A. M. Marconnet, *ACS Appl. Polym. Mater.* 2020

Advanced Flexible Heat Spreaders

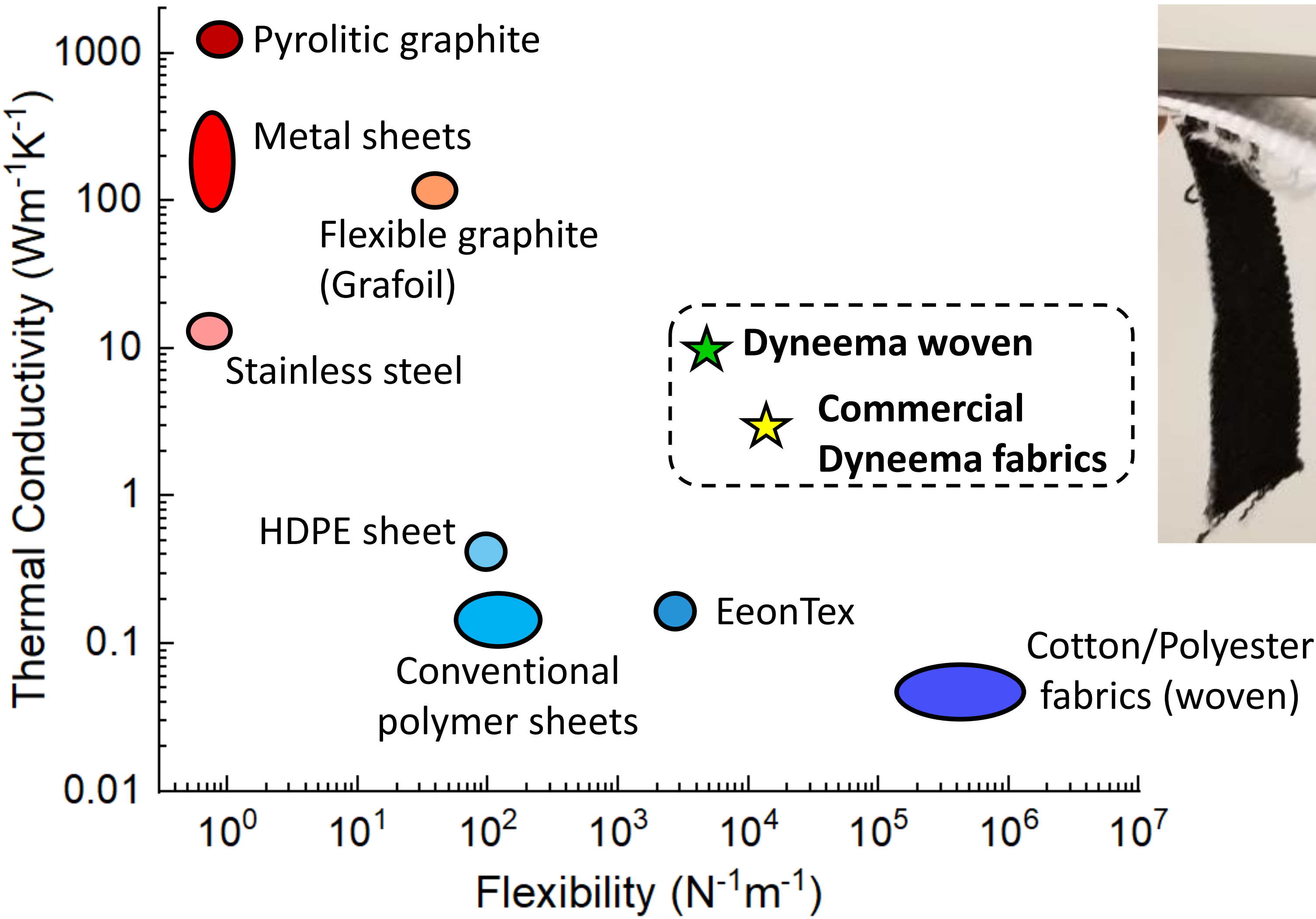
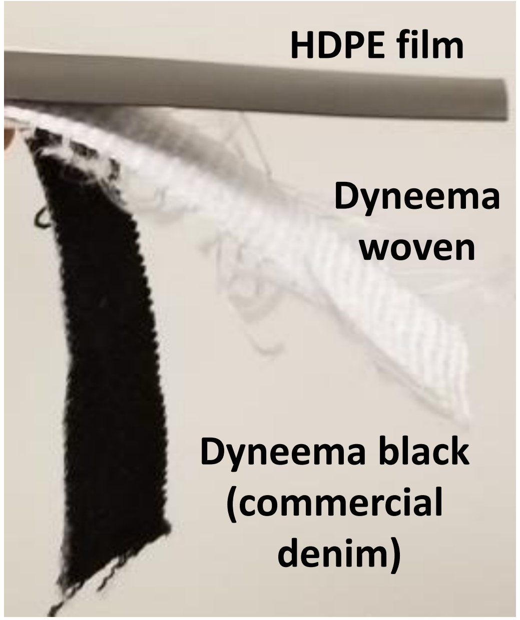


Illustration of bending under self weight

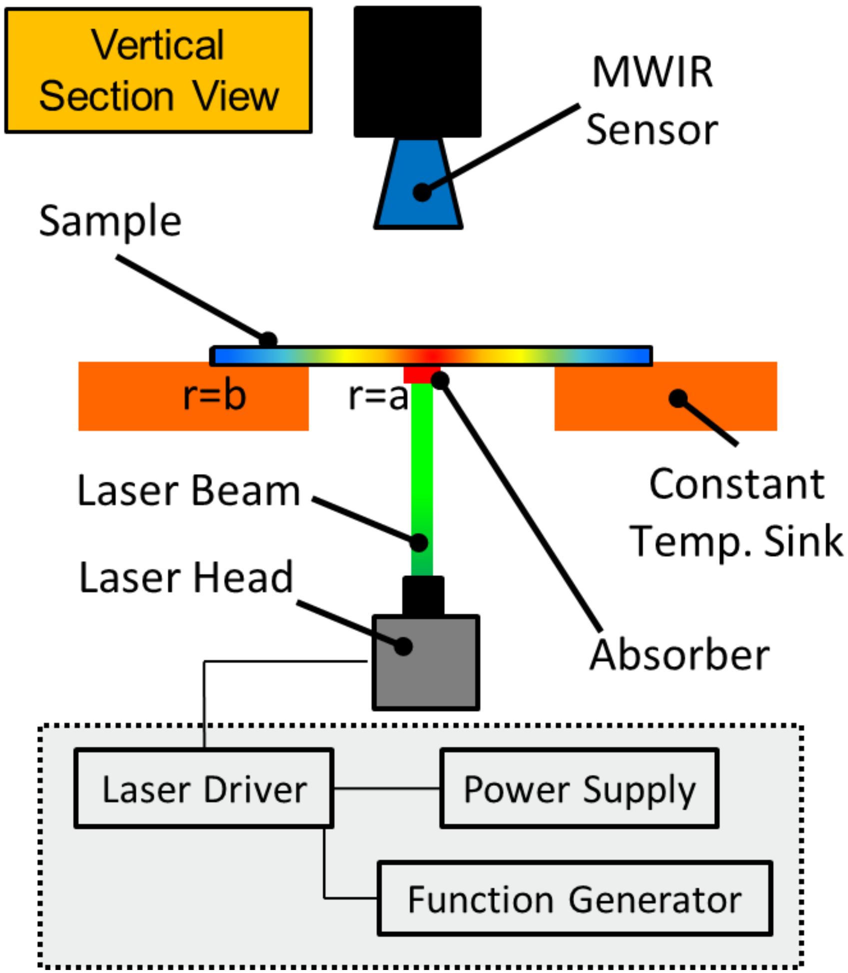


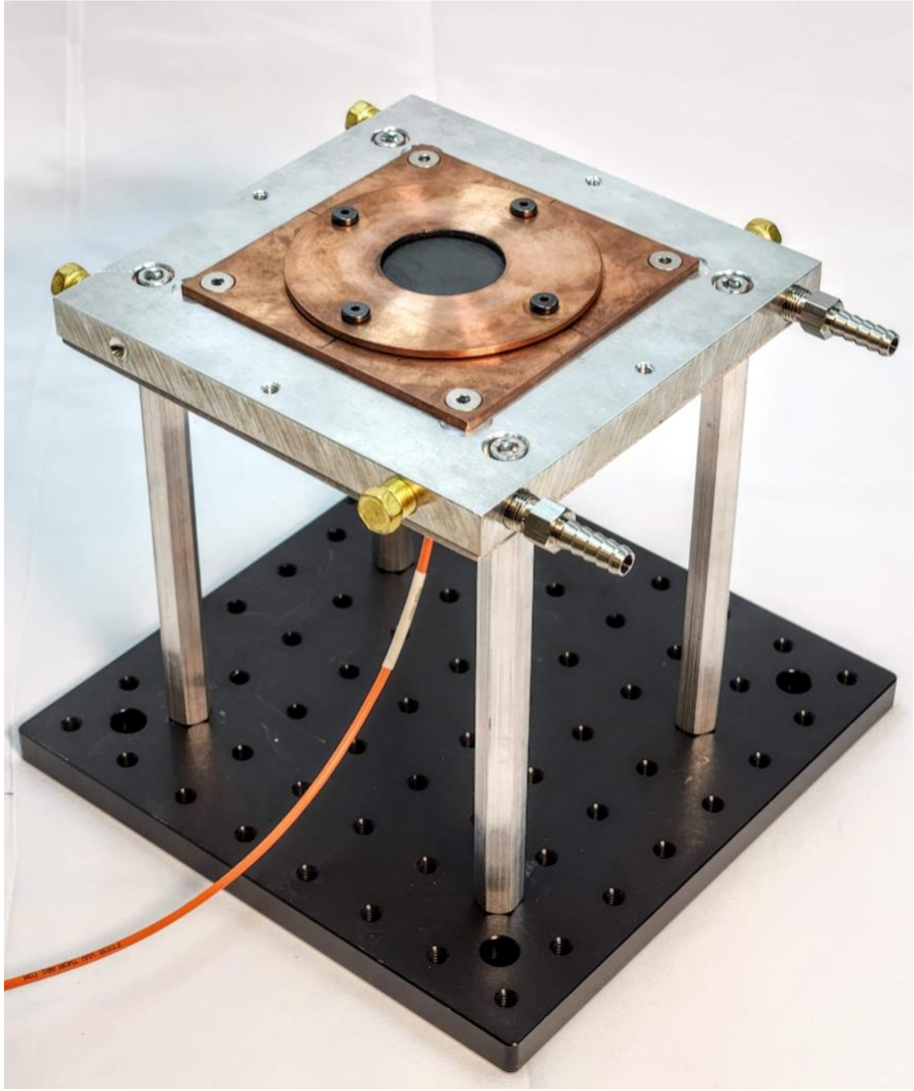
For all general materials, **thickness = 500 µm (approx. thickness of characterized fabrics)*

A.A. Candadai, J. A. Weibel, and A. M. Marconnet, *ACS Appl. Polym. Mater.* 2020

Anisotropic Property Characterization

The 1D IR Enhanced Angstrom method is extended to two dimensions for the measurement of thermal conductivity of films and sheets as a function of direction

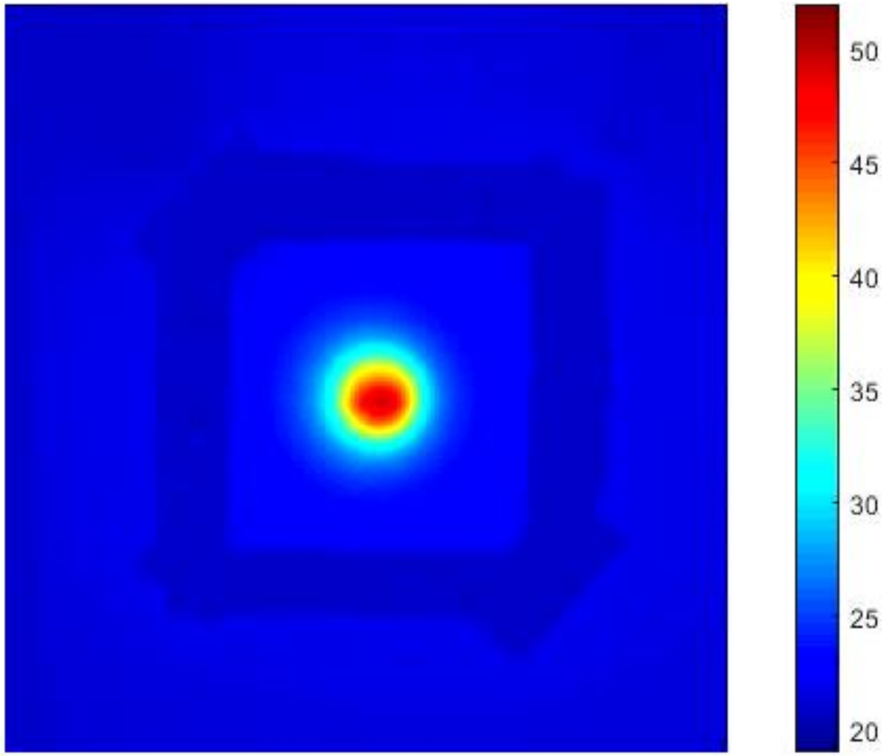




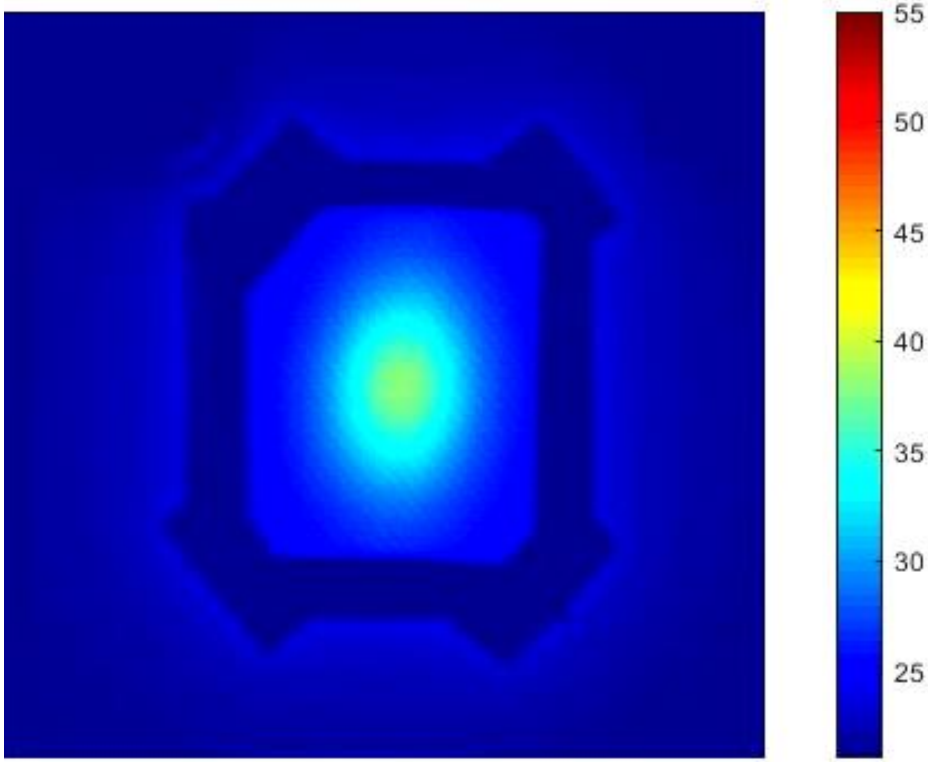
Hahn J. *et al*., A. Infrared microscopy enhanced Angstrom's method for thermal diffusivity of polymer monofilaments and films. J. Heat Transfer 141, (2019). DOI:10.1115/1.4043619

Anisotropic Property Characterization

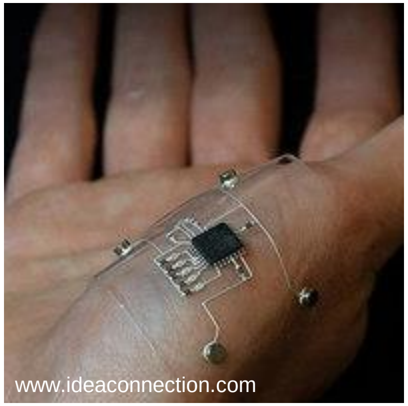
Isotropic, low *k*



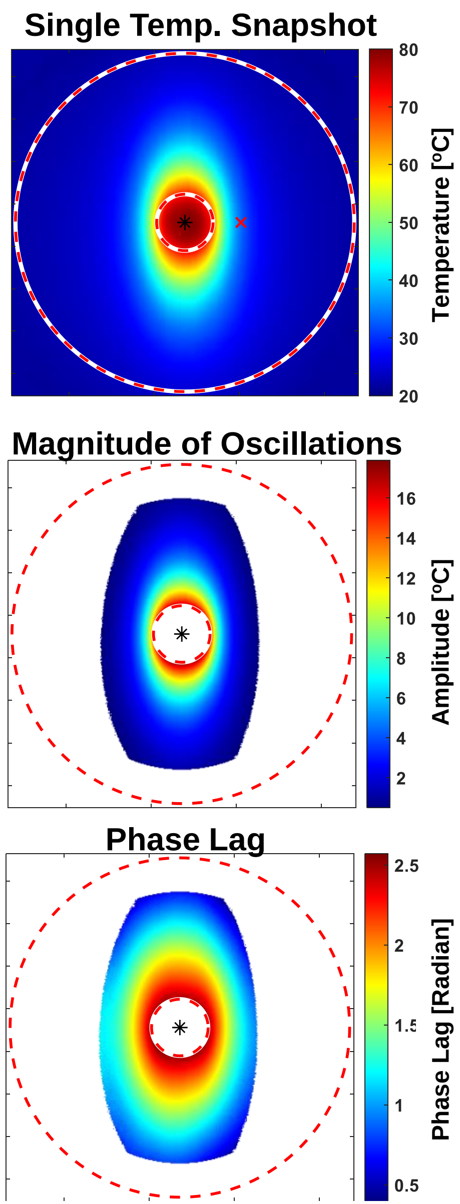
Anisotropic, high *k*

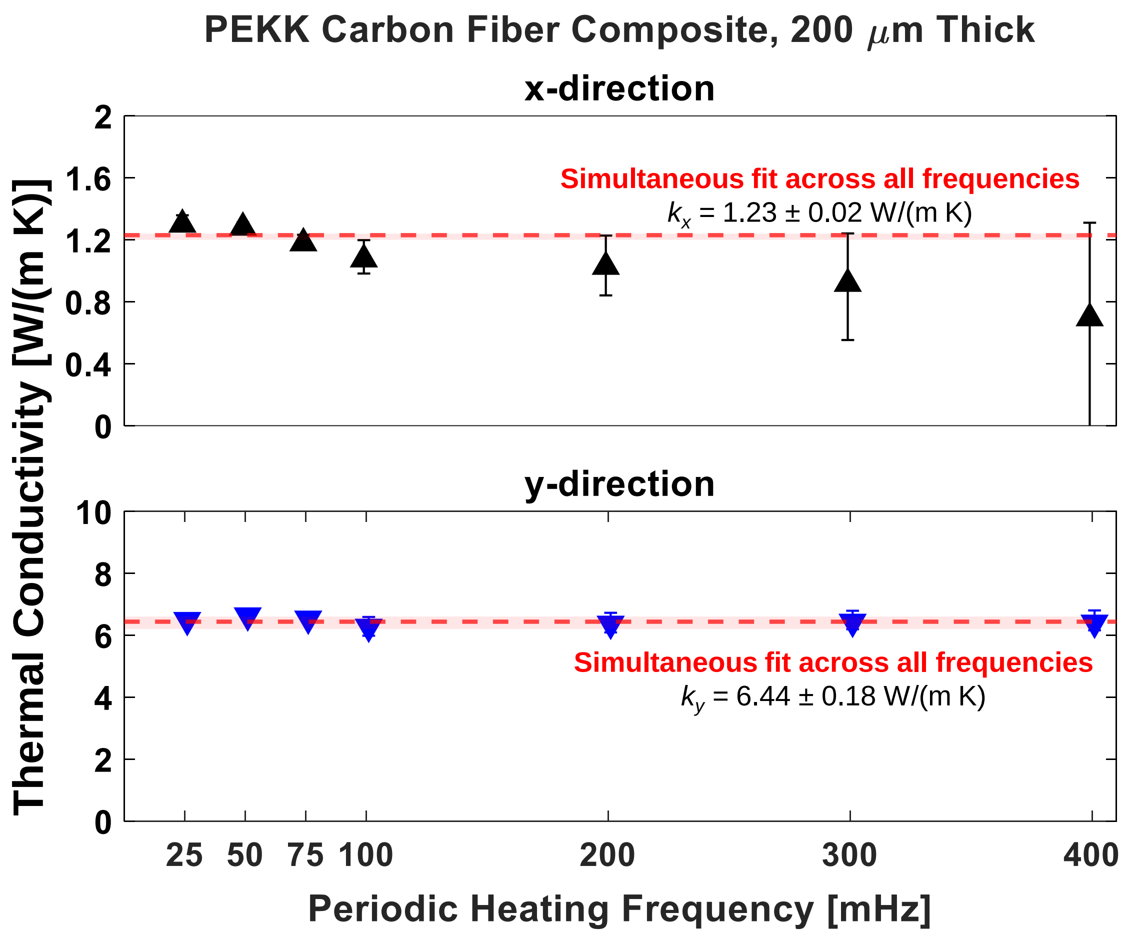


- Characterize and optimize material properties for composite heat spreaders
- Integrate flexible high conductivity heat spreaders into wearable electronics or situations needing conformal heat spreading



PEKK-Carbon Fiber Composite



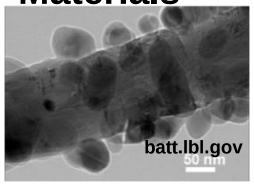


Key advantages of our method:

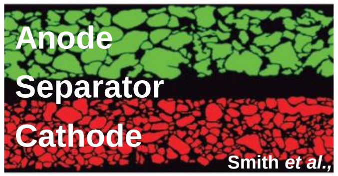
- Orthotropic thermal conductivity resolved in a single measurement without significant sample preparation
- Measurements can be conducted in air (insensitive to convection)
- No knowledge of boundary conditions or heater power required
- Relatively insensitive to calibration of emissivity

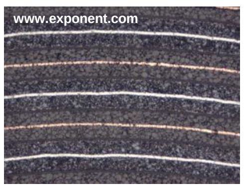
Li-Ion Battery: Thermal Management

Materials



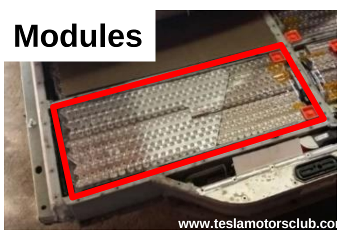
Electrodes



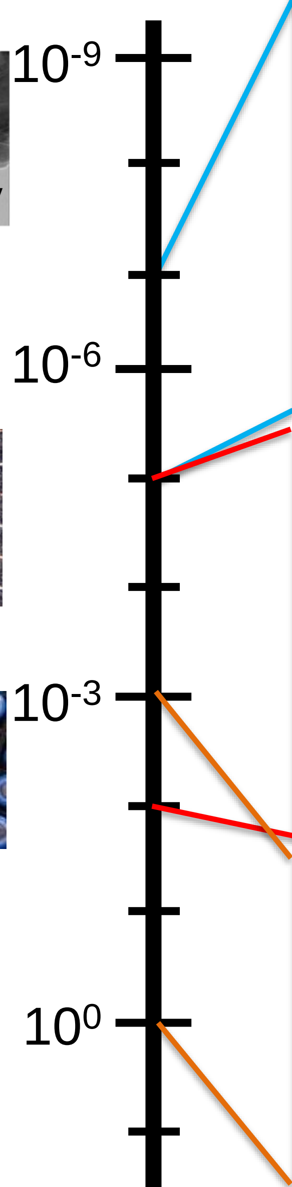


Cells

Modules

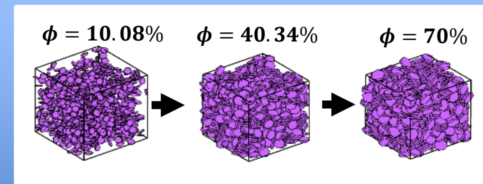


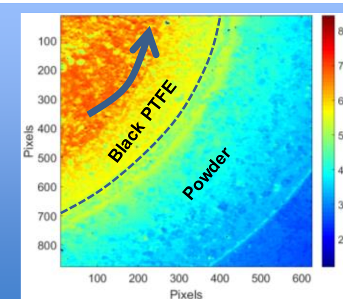
Packs



Length Scale [m]

Granular Mechanics & Thermal Transport

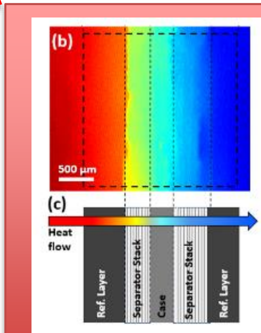




Experimental & computational efforts to engineer electrode processing to optimize performance. (Computations joint w/ Fisher)

Kantharaj *et al.*, *ITCC 2017*

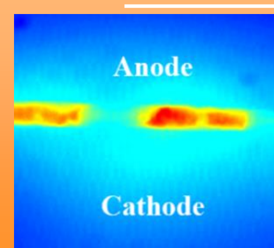
Thermal Property Analysis



- **Designed metrology techniques to measure thermal properties of Li-ion battery electrodes.**
- **First-of-kind direct measurements of thermal resistances within lithium-ion batteries**
- **Evaluation of wet/dry thermal conductivities**

Gaitonde *et al.*, *J. Power Sources*, 2017

Thermal Performance Analysis

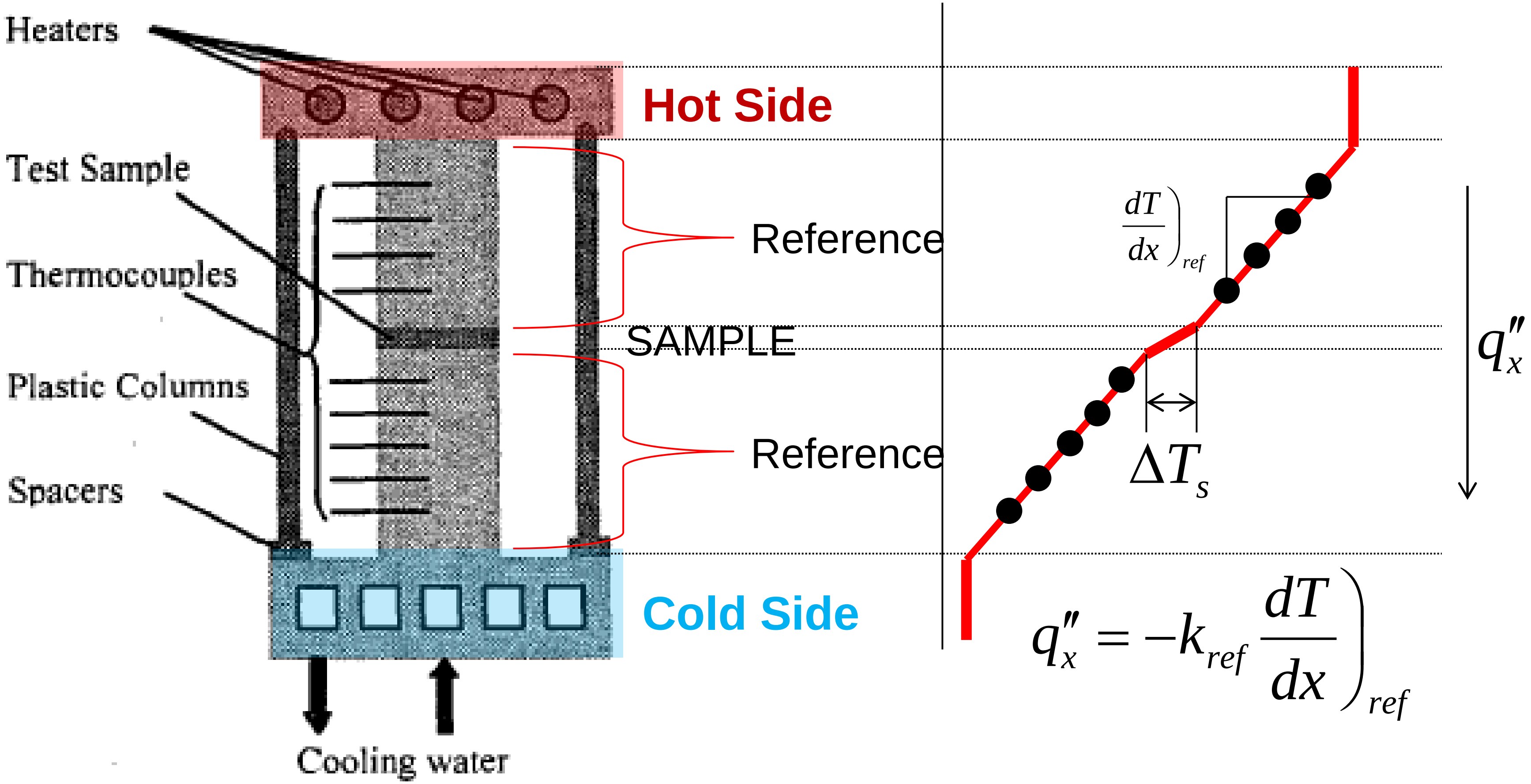


- **Experimental efforts to measure temperatures *in situ* during battery operation.**
- **Integration of property measurements into models of performance.**

Kantharaj *et al.*, *InterPACK*, 2018.

System Analysis: Immersion Cooling

ASTM D5470 Reference Bar Method

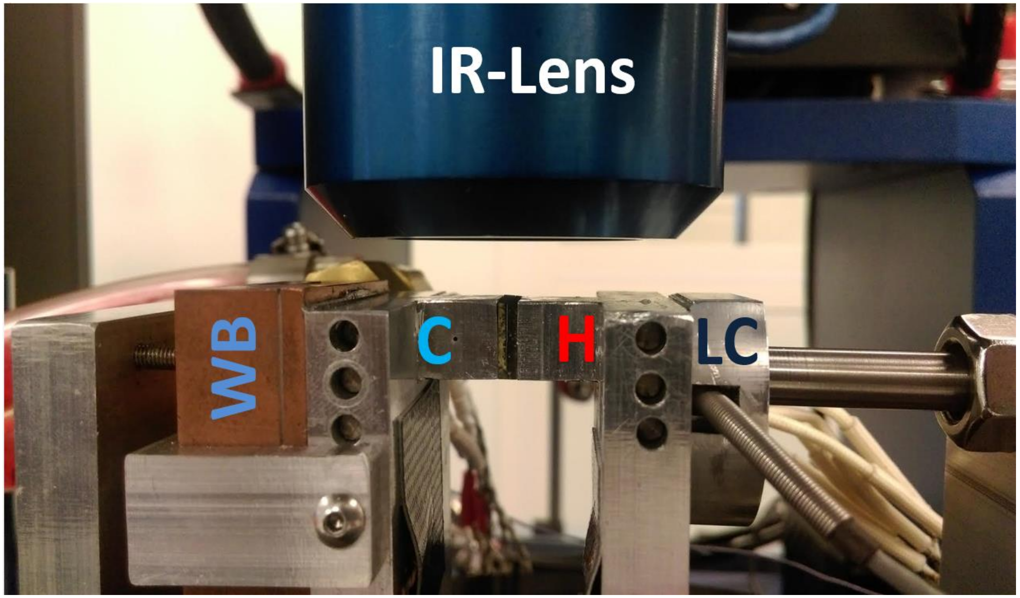


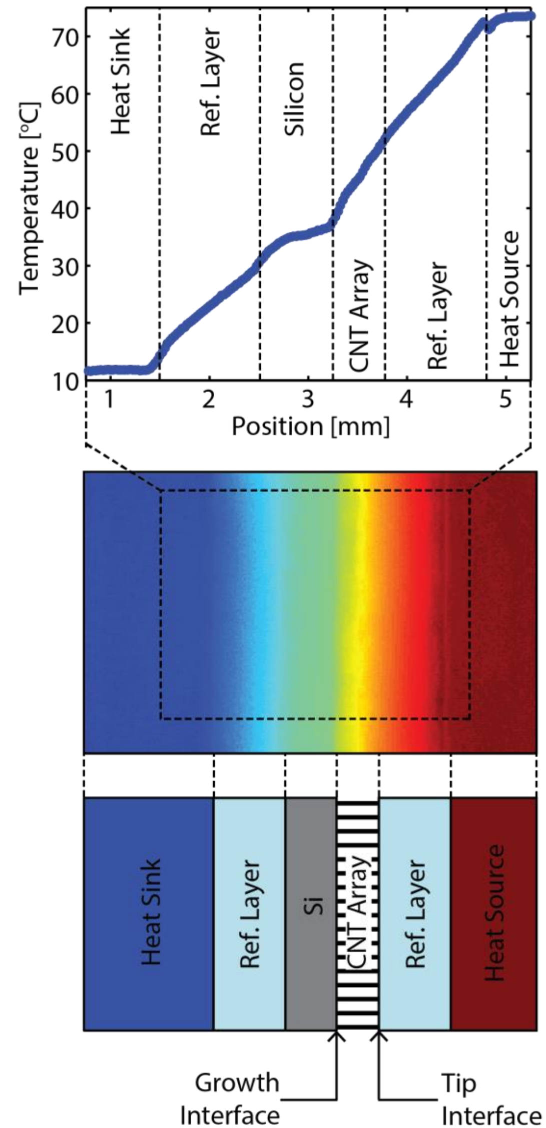
$$q_x'' = -k_{ref} \left.\frac{dT}{dx}\right)_{ref}$$

$$q_x = G_{th,s} \Delta T_s = \frac{k_s A}{L_s} \Delta T_s \rightarrow k_s = q_x'' L_s \big/ \Delta T_s$$

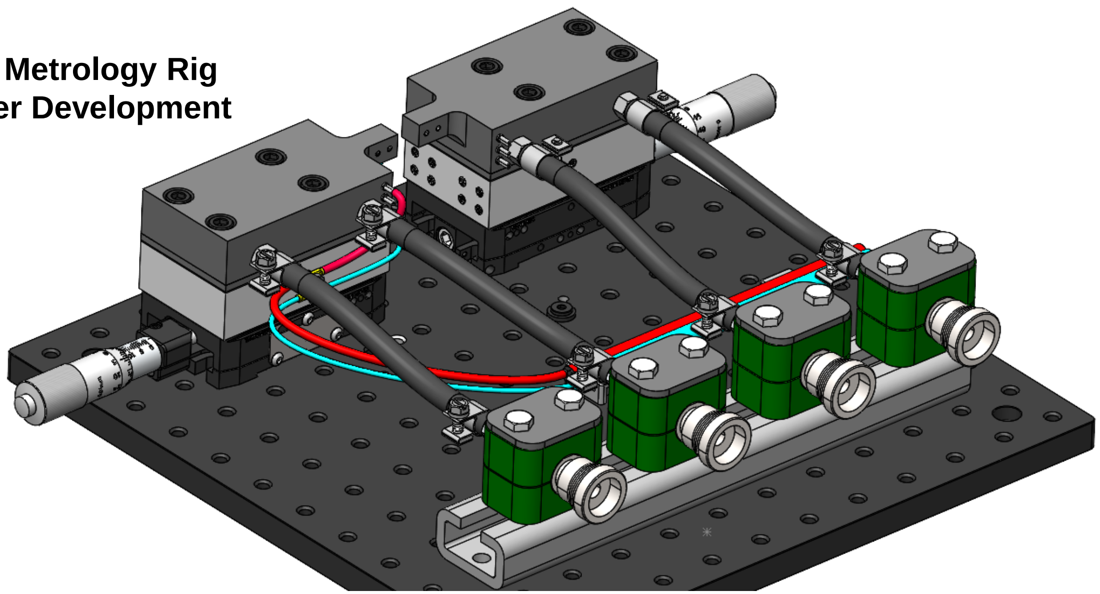
X. Hu, *et al.*, "Thermal conductance enhancement of particle-filled thermal interface materials using carbon nanotube inclusions," in *The Ninth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITHERM '04)*, 2004, pp. 63-69 Vol.1.

Miniaturized Infrared Thermal Metrology





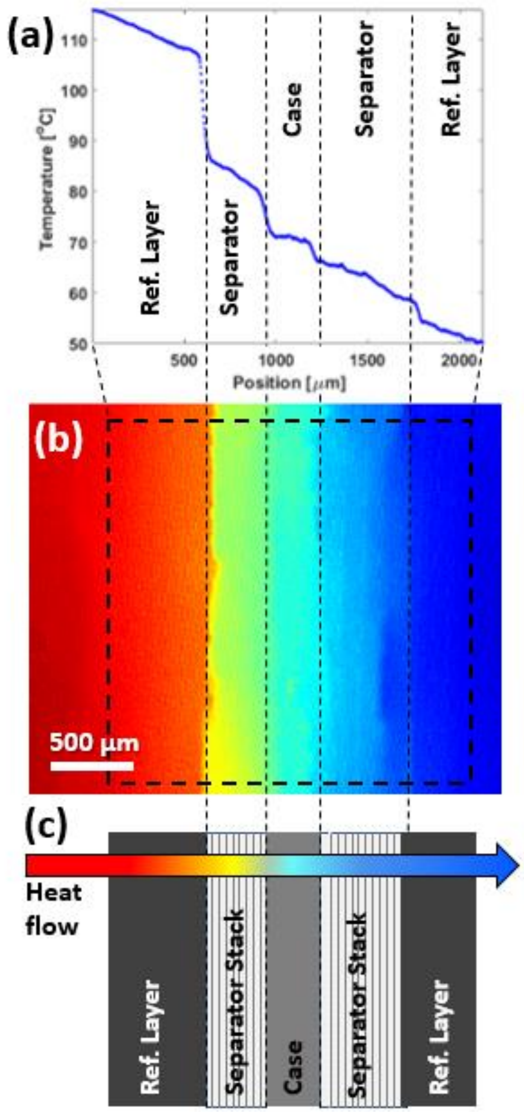
New Metrology Rig Under Development

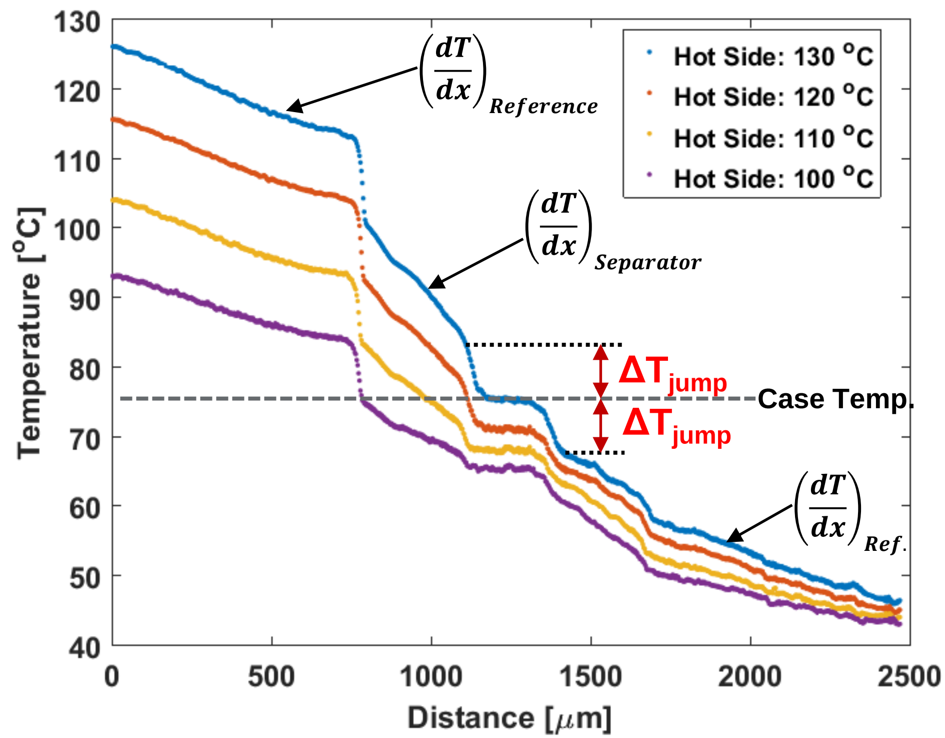


Gaitonde, Nimmagadda, **Marconnet**: "Measurement of Thermal Conductance in Li-ion Batteries " *Journal of Power Sources* (2017).
DOI: [10.1016/j.jpowsour.2017.01.019](https://doi.org/10.1016/j.jpowsour.2017.01.019)

Barako, M.T., Gao, Y., Won, Y., **Marconnet, A.**, Asheghi, M., and Goodson, K.E., *IEEE Transactions on Components, Packaging and Manufacturing Technology* (2014).
DOI: [10.1109/TCPMT.2014.2369371](https://doi.org/10.1109/TCPMT.2014.2369371)

Interfacial & Intrinsic Thermal Conductance



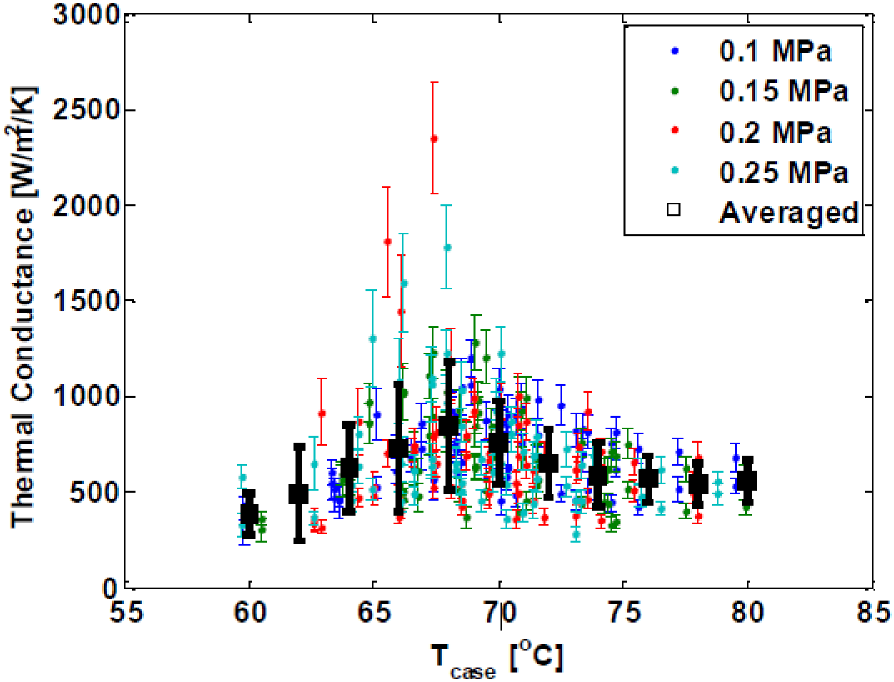


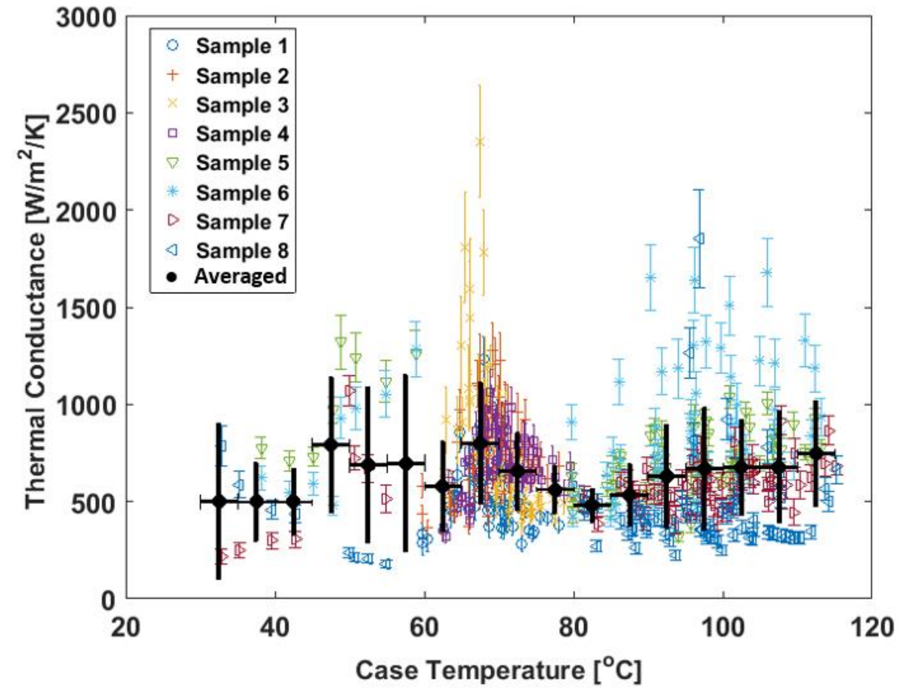
Temperature gradients across the sample stack, at four case temperatures

$$Thermal\ Conductance, G = \frac{q''}{\Delta T_{jump}}$$

Gaitonde, Nimmagadda, **Marconnet**: "Measurement of Thermal Conductance in Li-ion Batteries" *Journal of Power Sources* (2017).

Interfacial Thermal Conductance





- **Interfaces Measured: 8**
- **Pressure Range: 0.1-0.25 MPa**
- **Case Temperatures: 30-120 °C**

Mean Thermal Conductance: 670 W/(m²K)
Standard Deviation: 275 W/(m²K)

Gaitonde, Nimmagadda, **Marconnet**: “Measurement of Thermal Conductance in Li-ion Batteries ” *Journal of Power Sources* (2017).

Beyond Steady State: Phase Change Materials

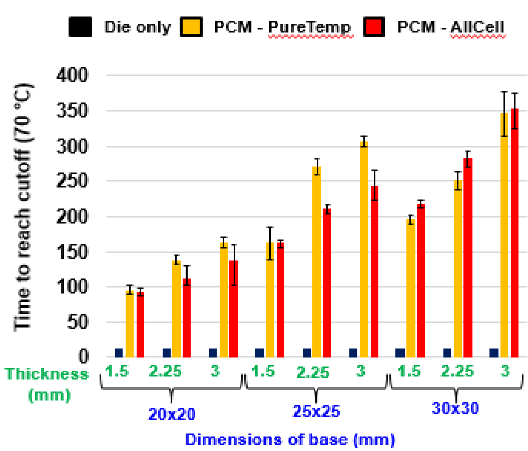
Commercial PCMs

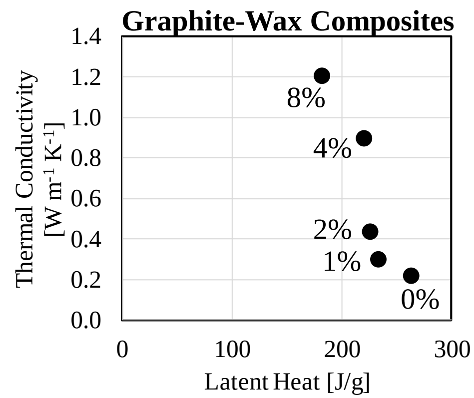
Composites

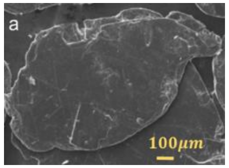
3D Package Designs

Database including over 500 PCMs ranked by:

$$FoM_q \sim \sqrt{\kappa_l \rho_l L_w}$$



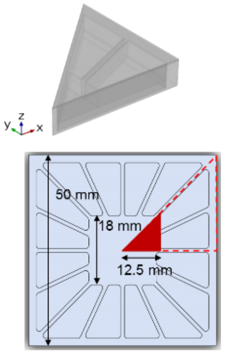


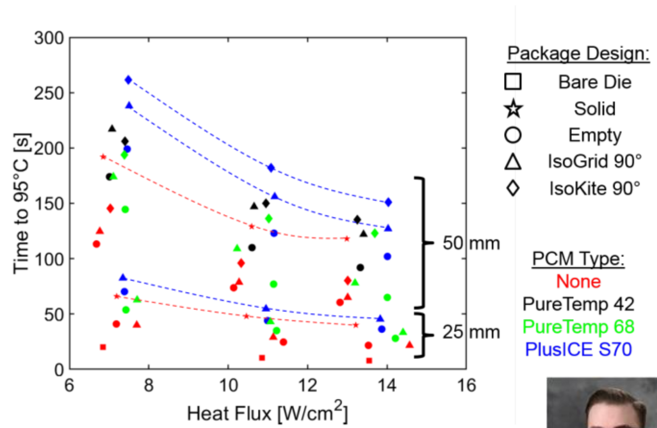


High Latent Heat

+

High Conductivity Pathways

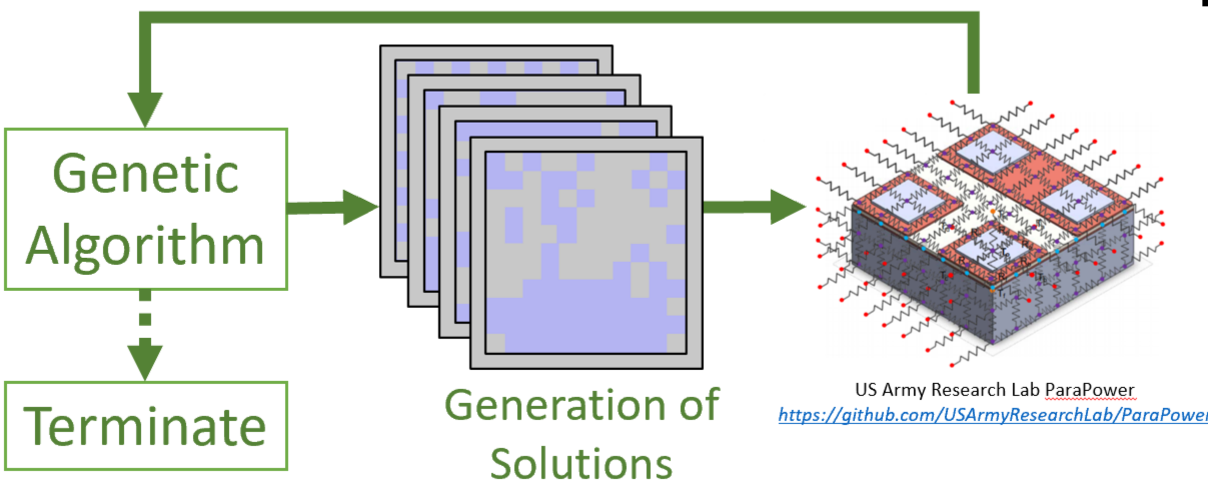




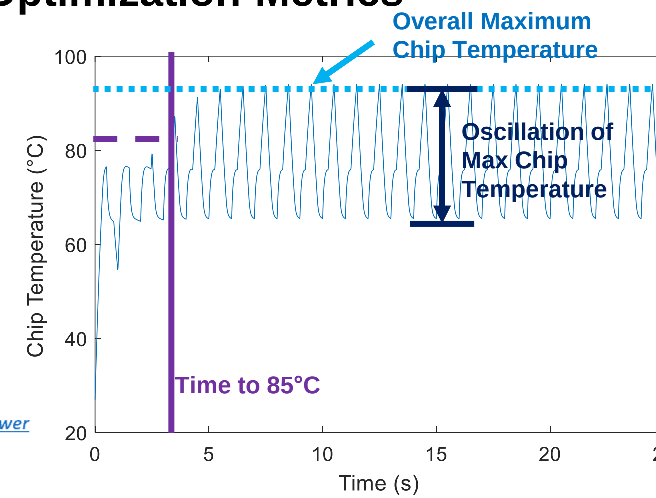
Collier Miers
PhD 2019
Now at JPL

CTRC Projects w/ John Howarter

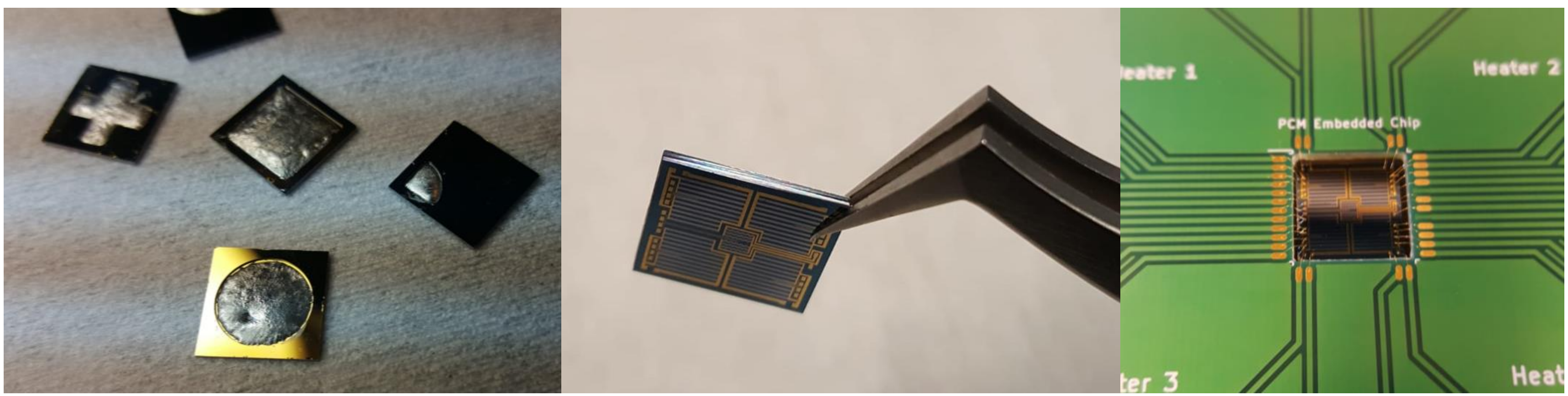
Embedded Cooling + ML Optimization



Optimization Metrics



Experimental Evaluation (in progress):



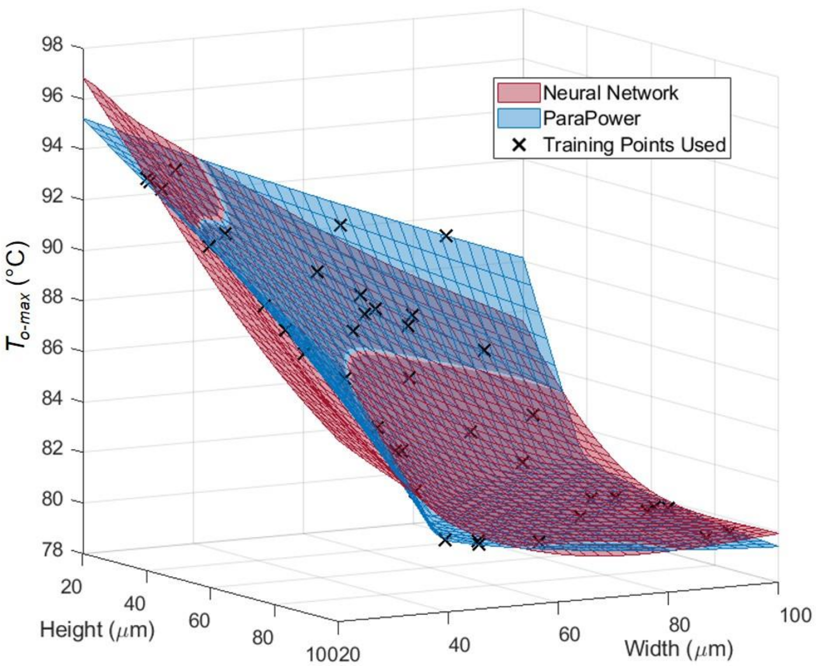
References: Bhatasana & Marconnet, “Optimization of an Embedded Phase Change Material Cooling Strategy Using Machine Learning”, *ITherm 2021*

Bhatasana & Marconnet, “Machine-Learning Assisted Optimization Strategies for Phase Change Materials Embedded within Electronic Packages”, *Applied Thermal Engineering*, 2021.

Bhatasana& Marconnet, *Electronics Cooling Magazine,* http://bit.ly/EmbeddedCooling

Beyond Conventional Optimization Strategies

- Machine learning based optimization strategies (e.g., Genetic Algorithms) reduce time to optimize solution
- Reduced complexity models, such as ParaPower over COMSOL, increase efficiency and training Neural Networks on limited data sets can further enhance optimization



PCM Silicon

References: Bhatasana & Marconnet, "Optimization of an Embedded Phase Change Material Cooling Strategy Using Machine Learning", *ITherm 2021*

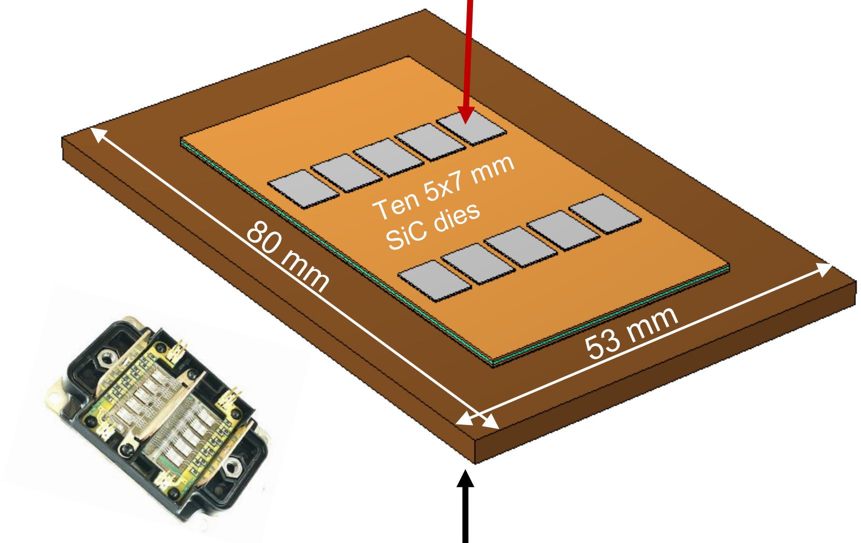
Bhatasana & Marconnet, "Machine-Learning Assisted Optimization Strategies for Phase Change Materials Embedded within Electronic Packages", *Applied Thermal Engineering*, 2021.

Bhatasana& Marconnet, *Electronics Cooling Magazine,* http://bit.ly/EmbeddedCooling

High Powered Electronics

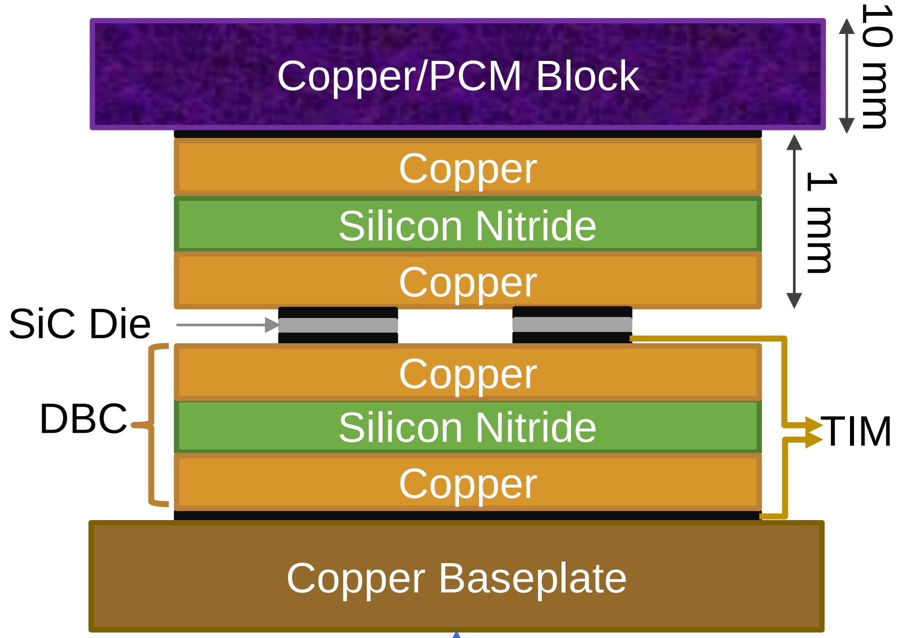
Baseline Architecture

Heating:
Heat distributed across SiC dies



Convective Cooling (Coldplate)
50/50 WEG at 0.4 lpm → 5,000 W/m²K
T_{in} = 65 °C

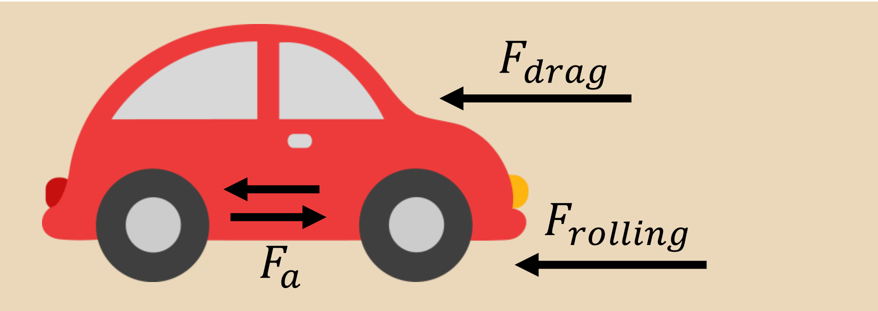
Hybrid Active+Passive Cooling
(1.5 Side Cooing)



Convective Cooling (Coldplate)
50/50 WEG at 0.4 lpm → 5,000 W/m²K
T_{in} = 65 °C

PE Module: Wolfspeed XM3. Coldplate: Wieland Microcool CP3012
Moreno et al. Electric-Drive Vehicle Power Electronics Thermal Management

Drive Cycle → Transient Heating



$$F_{Total} = F_{accleration} + F_{rolling} + F_{drag}$$

$$F_{accleration} = ma$$ (m → 2200 kg)

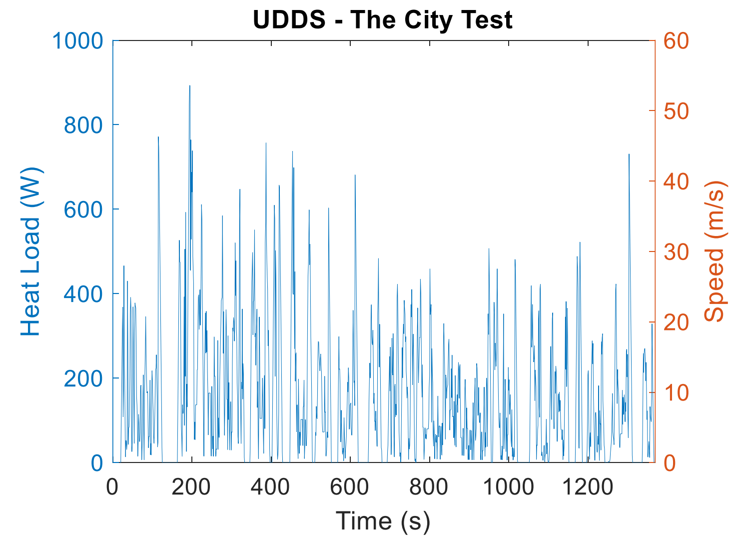
$$F_{rolling} = c_R mg$$ (c_R → 0.015)

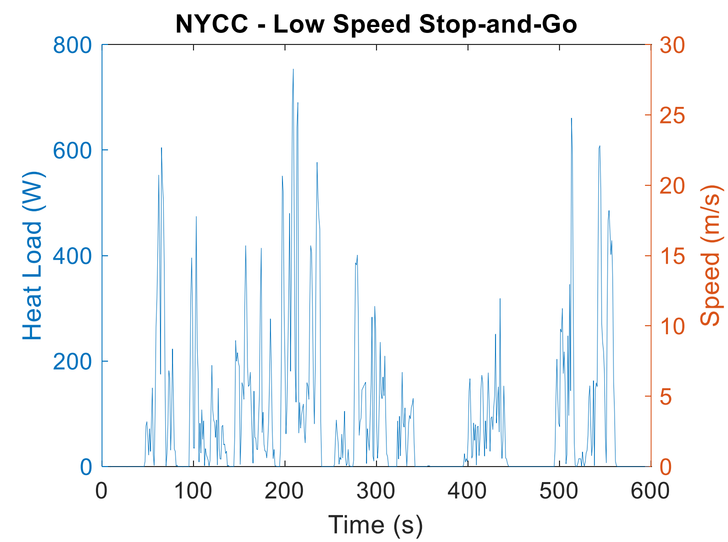
$$F_{drag} = \frac{1}{2}\rho c_D A V^2$$ (c_D → 0.3; A → 0.58 m^2)

$$Heat\ Load = (1-\eta) \times |P|$$

(η → 98% efficiency; $|P|$ → Regenerative breaking)

$$\boldsymbol{Heat\ Load = (1-\eta) \times |VF|}$$

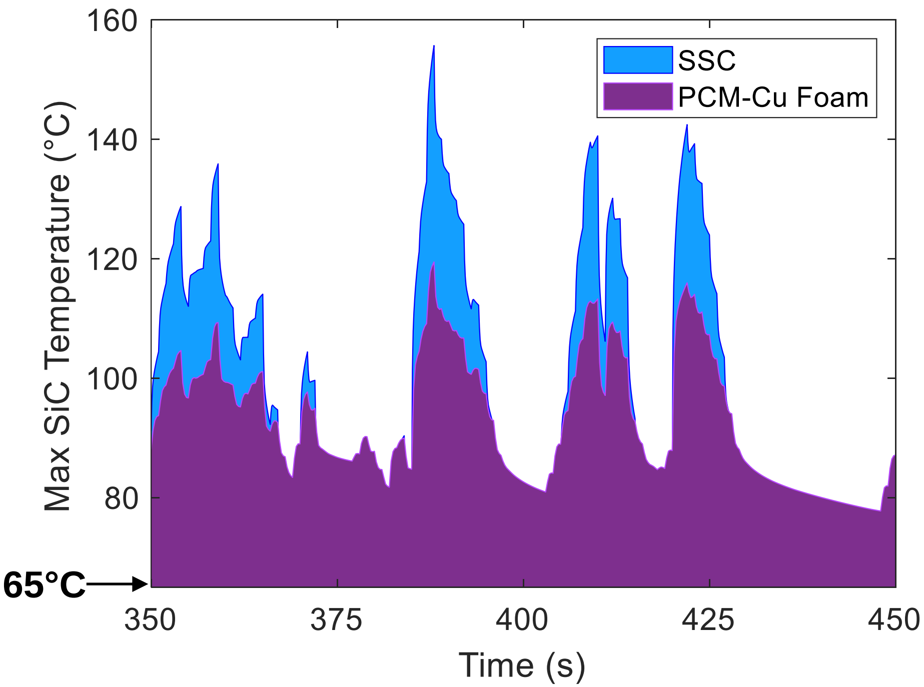




Hollis *et al.*, *Journal of Electronic Packaging*, 20201. https://doi.org/10.1115/1.4052669
Drive Cycles: https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules

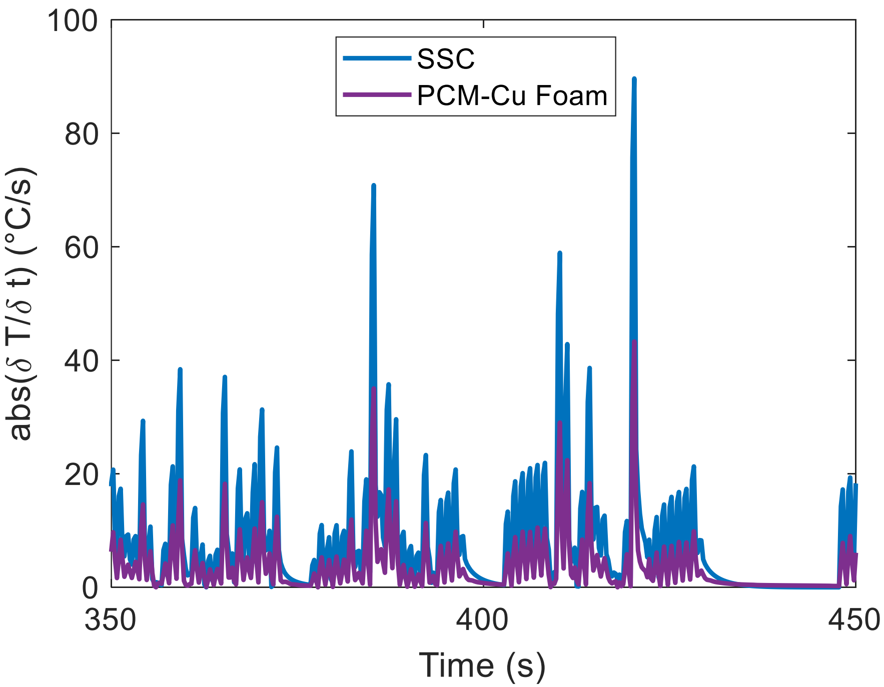
Metrics of System Performance

Average Elevated Temperature



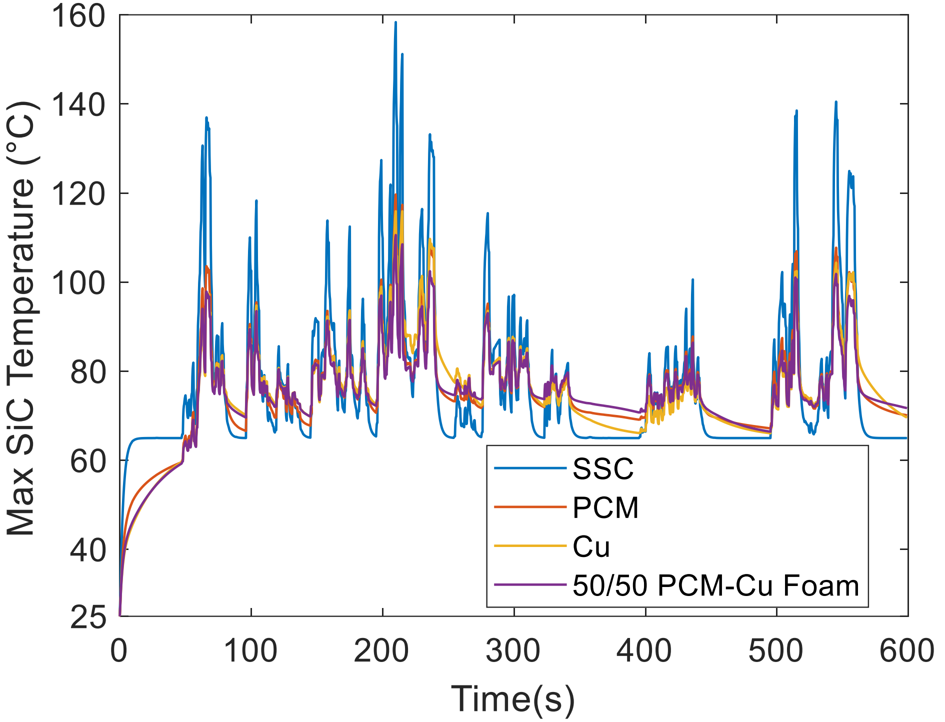
Metric	SSC	Foam
$\overline{\Delta T_{max>65°C}}$	30°C	29°C
$\sigma(T_{max>65°C})$	25°C	11°C

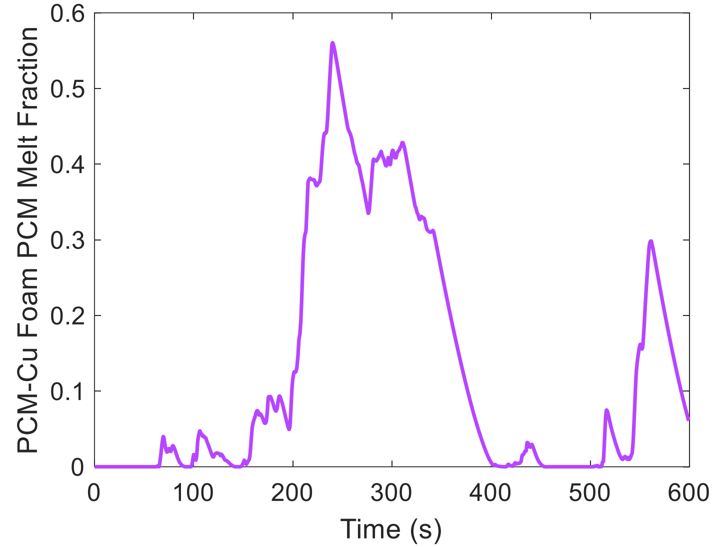
Derivative of Transient Temperature



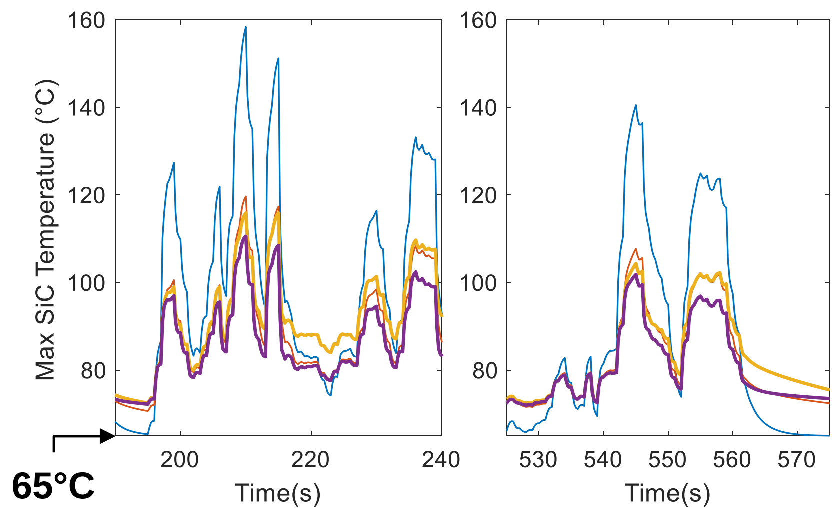
Metric	SSC	Foam
$\frac{\delta T}{\delta t}_{max}$	90°C	43°C

Improved Transient Performance - NYCC





PCM Mitigates Impact of Large Power Spikes

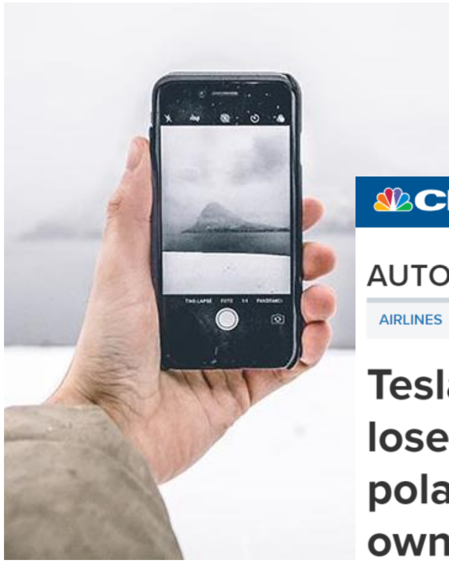


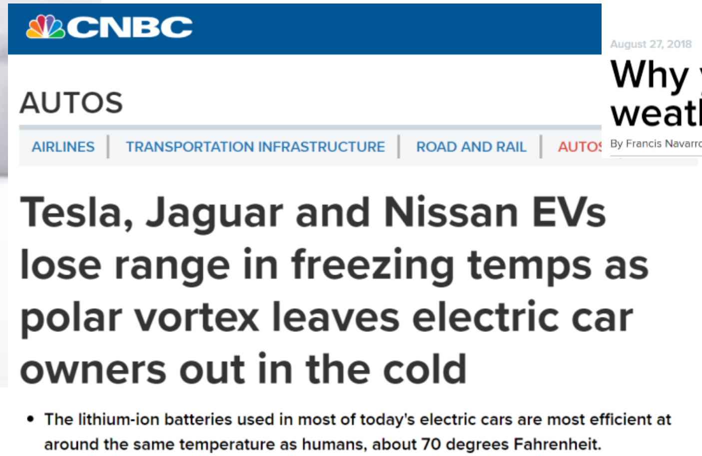
Metric	SSC	PCM	Cu	50/50 Foam
$\overline{\Delta T_{max>65°C}}$	13°C	12°C	12°C	12°C
$\sigma(T_{max>65°C})$	17°C	8.9°C	9.0°C	7.3°C
$\delta T/\delta t_{max}$	83°C/s	43°C/s	40°C/s	38°C/s

Open Questions for PCM Optimization

- How much can we the reduce flow rate of the cooling fluid and achieve similar performance metrics?
- What is the optimum volume fraction of the PCM with foam?
- Can we reduce the weight and cost of the system while maintaining performance using the hybrid approach?

Thermal Switches

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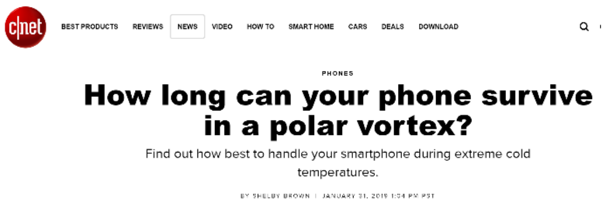
AIRLINES | TRANSPORTATION INFRASTRUCTURE | ROAD AND RAIL | AUTOS

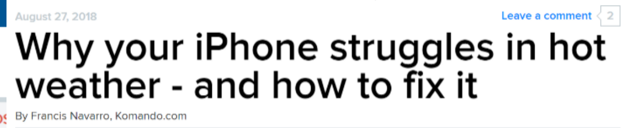
Tesla, Jaguar and Nissan EVs lose range in freezing temps as polar vortex leaves electric car owners out in the cold

- The lithium-ion batteries used in most of today's electric cars are most efficient at around the same temperature as humans, about 70 degrees Fahrenheit.


PHONES

How long can your phone survive in a polar vortex?

Find out how best to handle your smartphone during extreme cold temperatures.

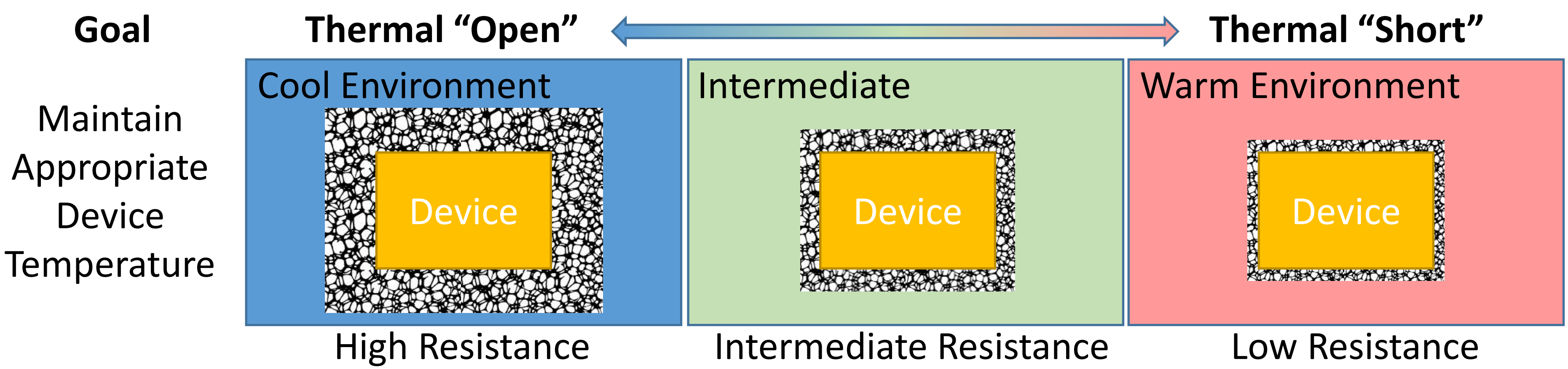

August 27, 2018

Leave a comment 2

Why your iPhone struggles in hot weather - and how to fix it

By Francis Navarro, Komando.com

Dynamic and Continuous Thermal Switch

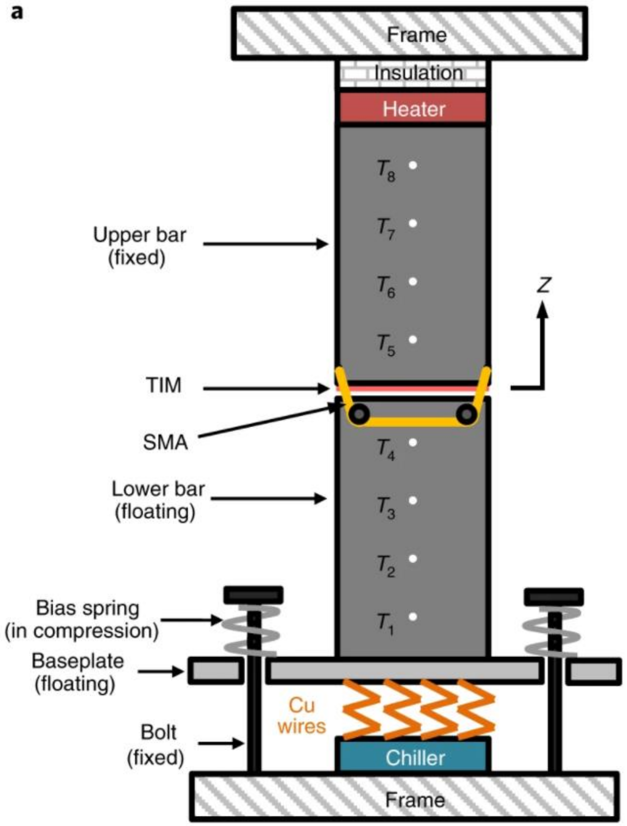


Du, ..., Marconnet, and Ruan, *Nat. Comm.*, **12**, 4915 (2021). DOI:10.1038/s41467-021-25083-8

Thermal Switches

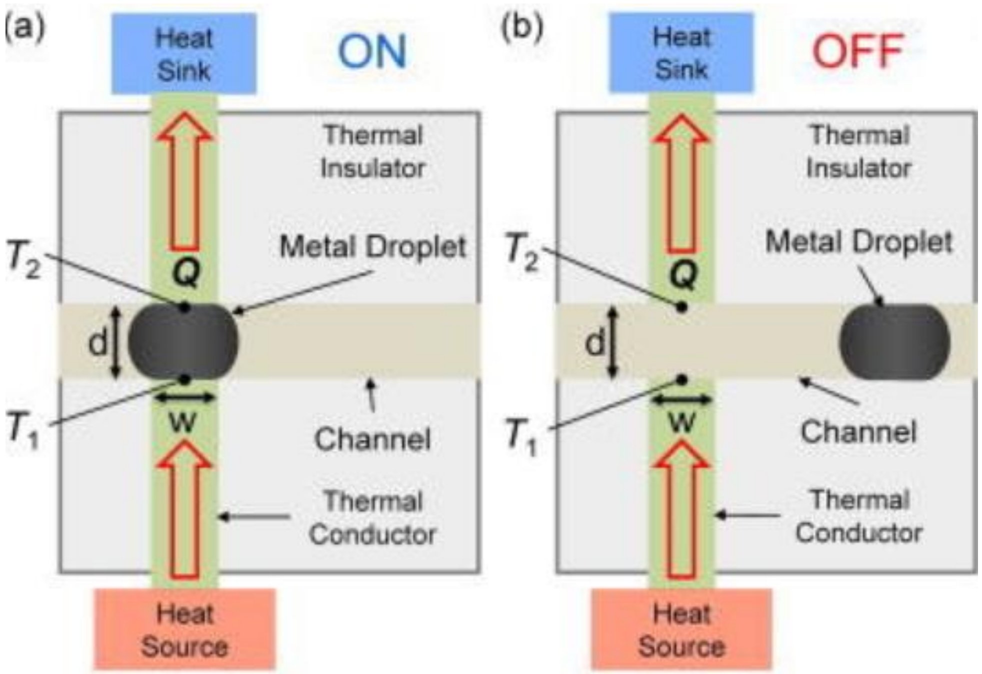
Make and Break Contact → High Switching Ratio

Shape Memory Alloy



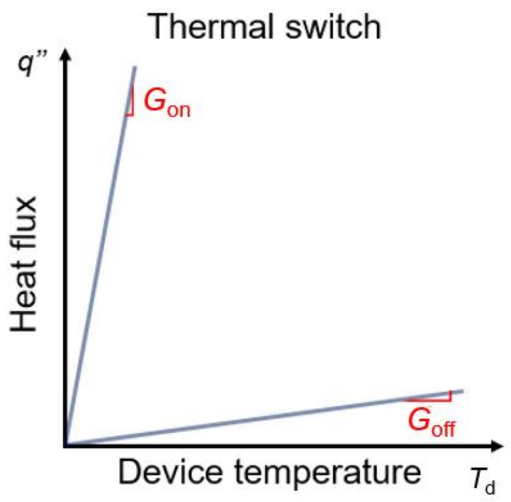
Hao *et al. Nature Energy* **3**, 899-906 (2018)

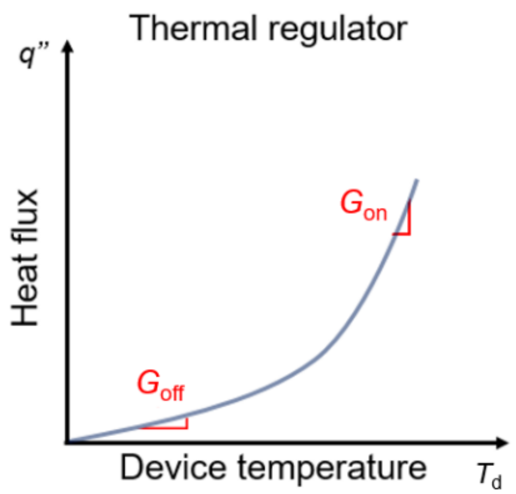
Liquid Metal Droplet

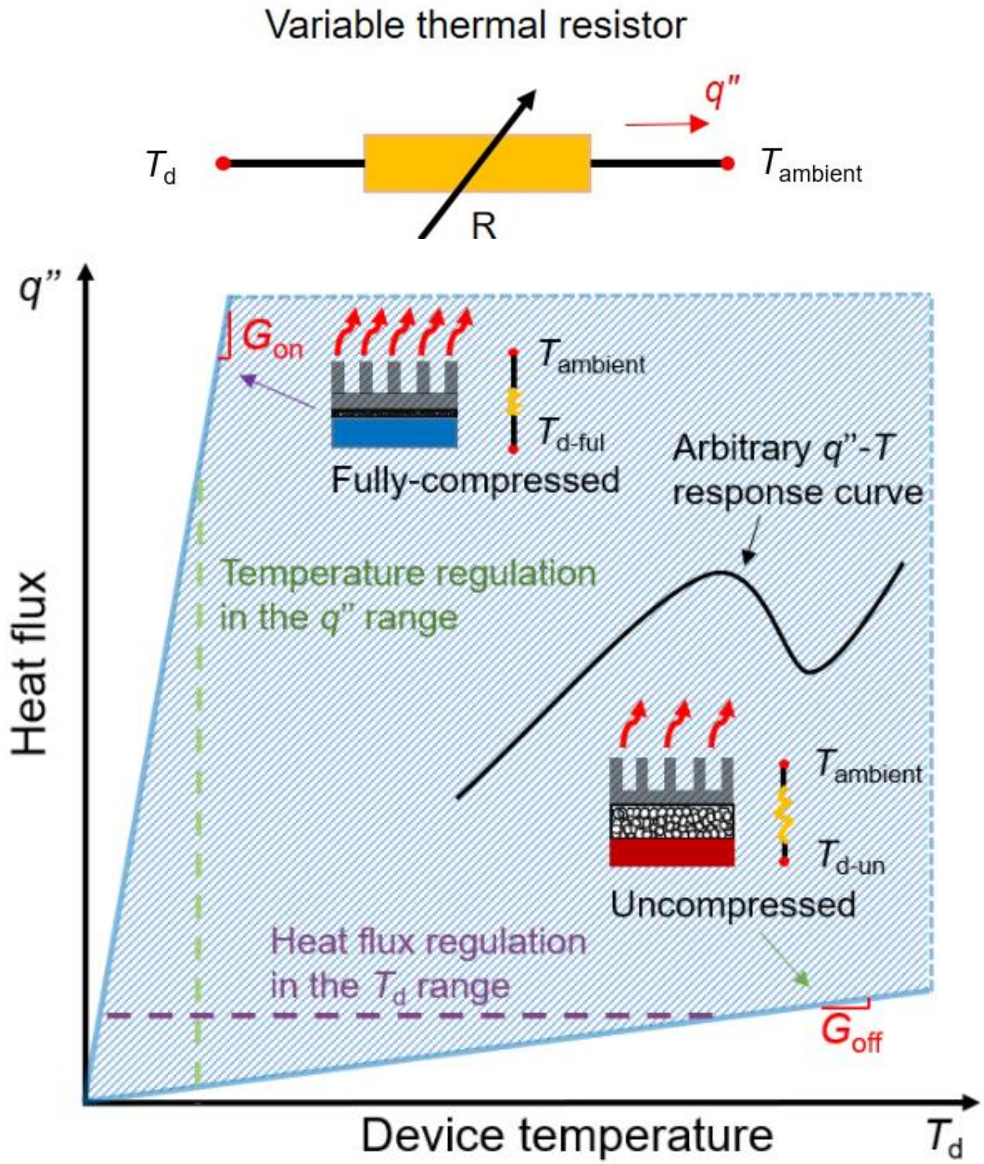


Yang *et al. Appl. Phys. Lett*. **112**,063505 (2018)

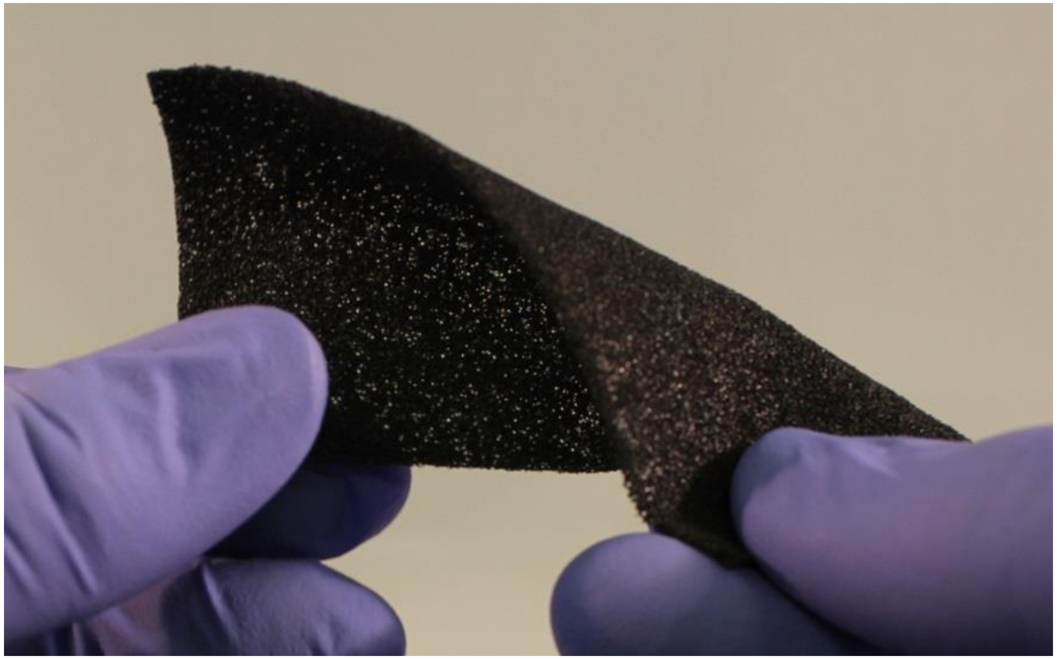
Continuously Variable Thermal Resistance

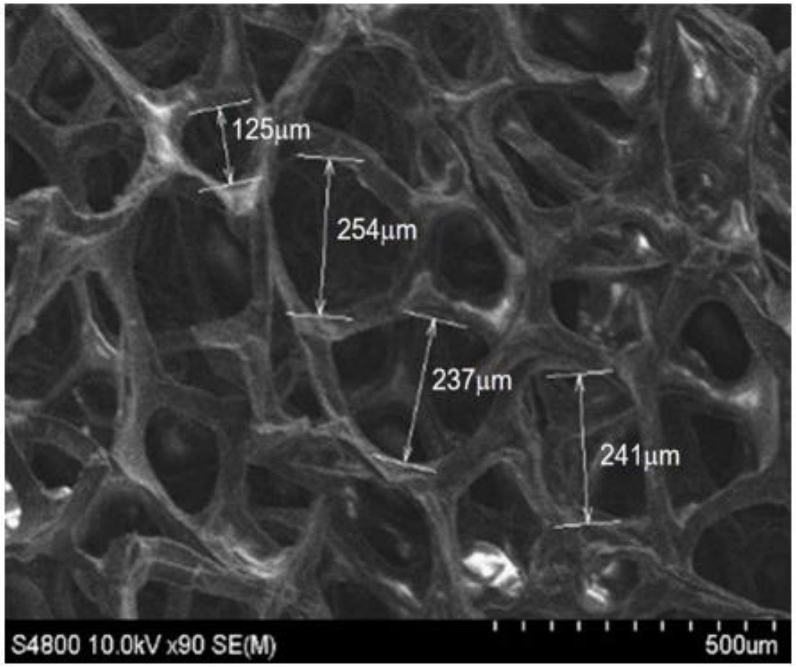




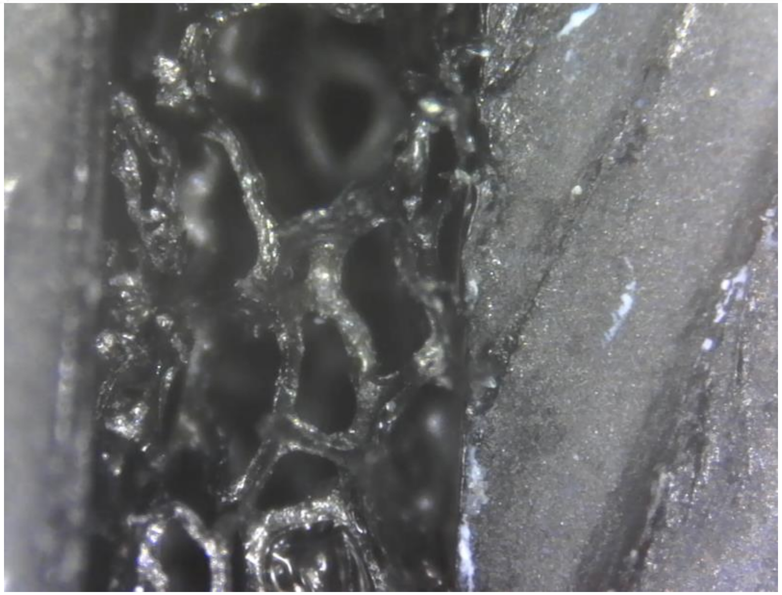


Compressible Graphene Foam





- CVD grown Graphene foam (95%) embedded with PDMS (5%)
- Open cell foam structure deforms upon compression



Characterizing Thermal Properties

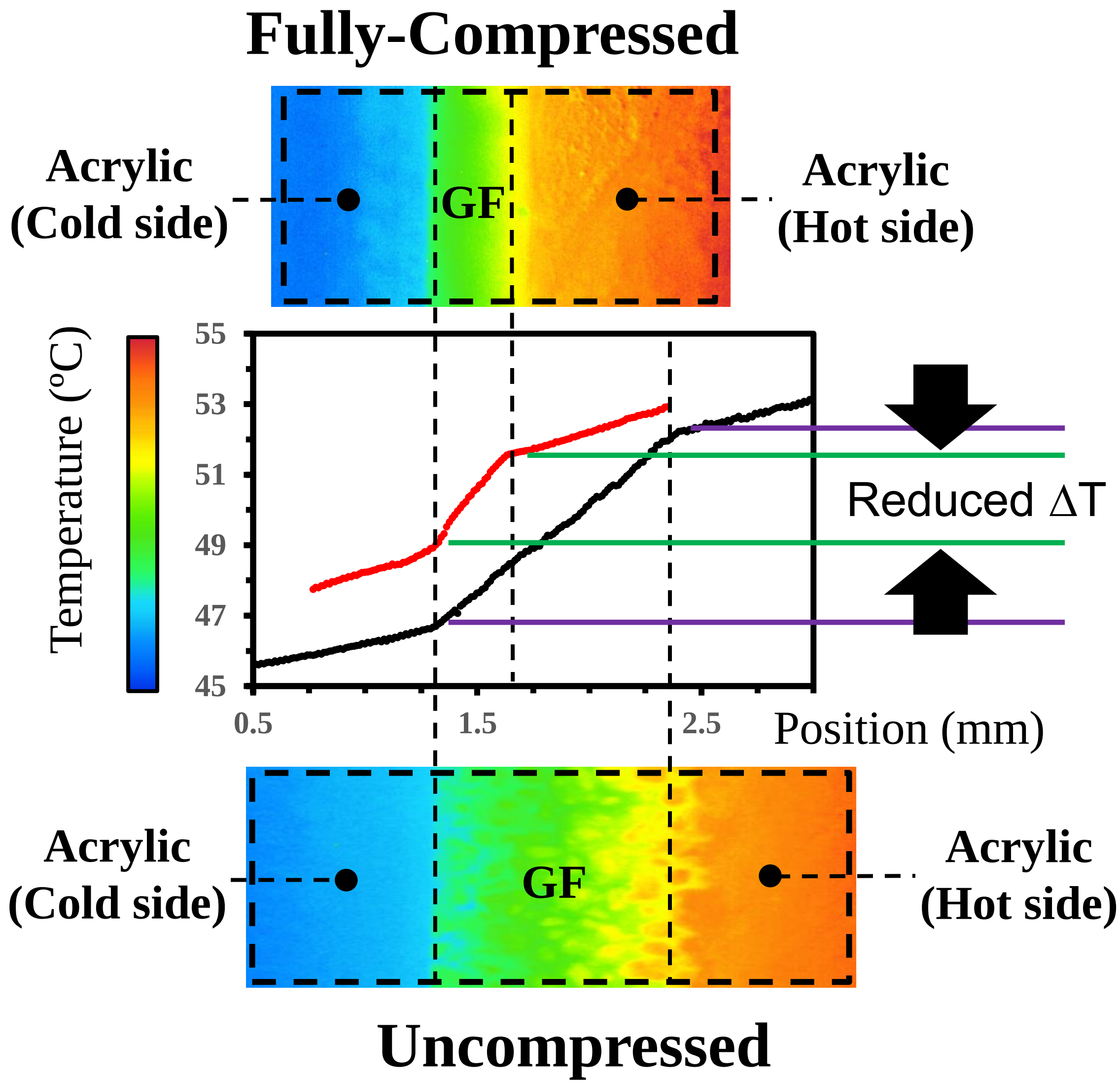
- At each level of compression, emissivity map is re-calibrated
- Heat flow established across the sample
- Same analysis procedure is applied at every strain

Conductance

$$G_{sample} = \frac{q}{\Delta T} \approx \frac{k_{sample}}{L} = \frac{1}{R''_{th}}$$

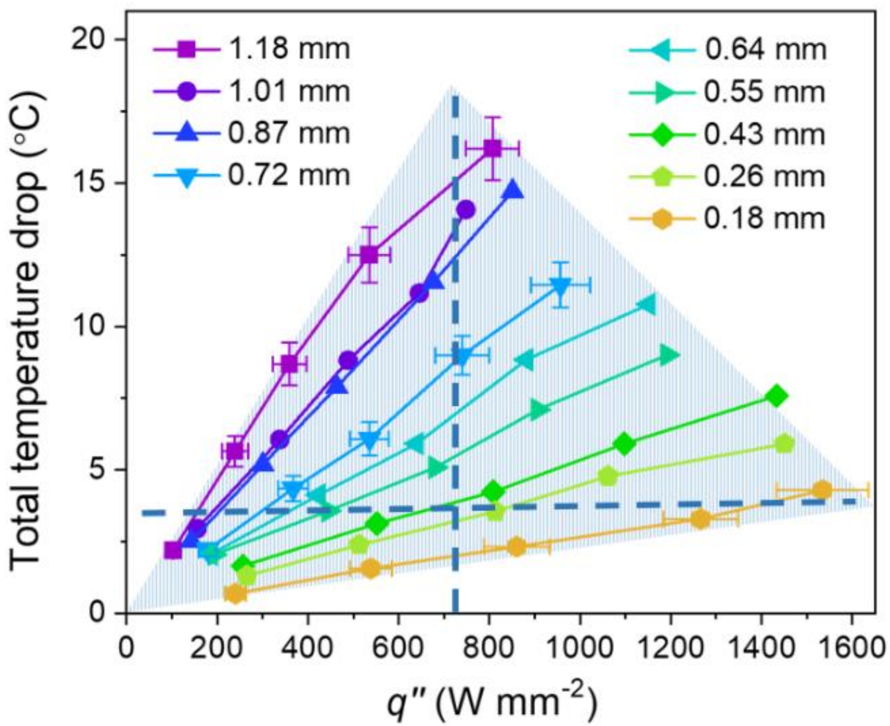
Conductance Ratio

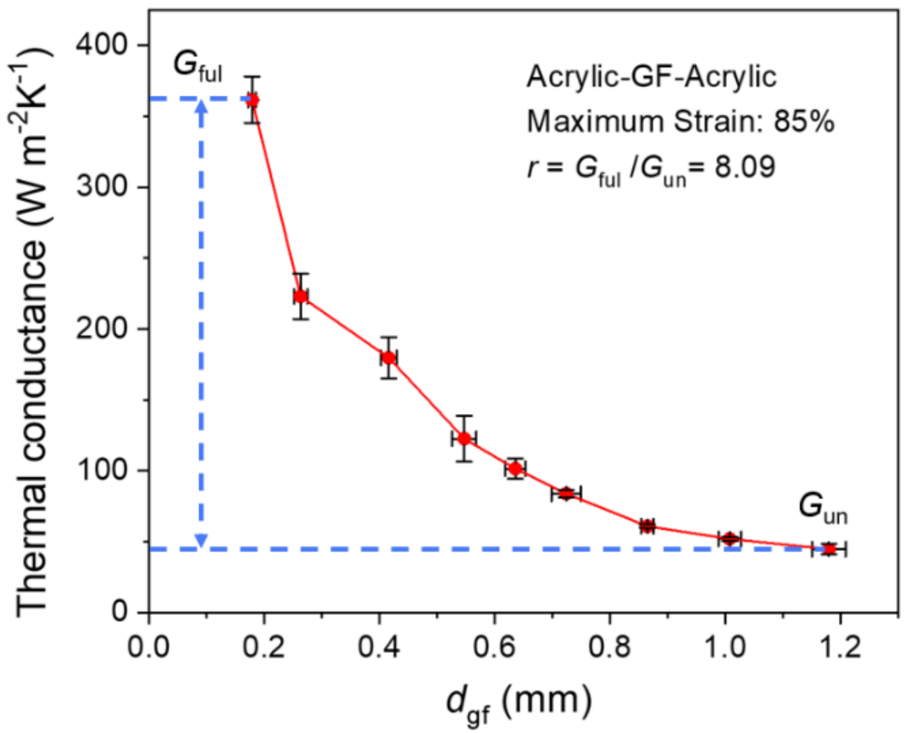
$$r = \frac{G_{Fully-Compressed}}{G_{uncompressed}}$$



Du *et al.*, *Nat. Comm.*, **12**, 4915 (2021). DOI:10.1038/s41467-021-25083-8

Variable Thermal Conductance





Conductance

$$G_{sample} = \frac{q}{\Delta T} \approx \frac{\mathrm{k_{sample}}}{L} = \frac{1}{R''_{th}}$$

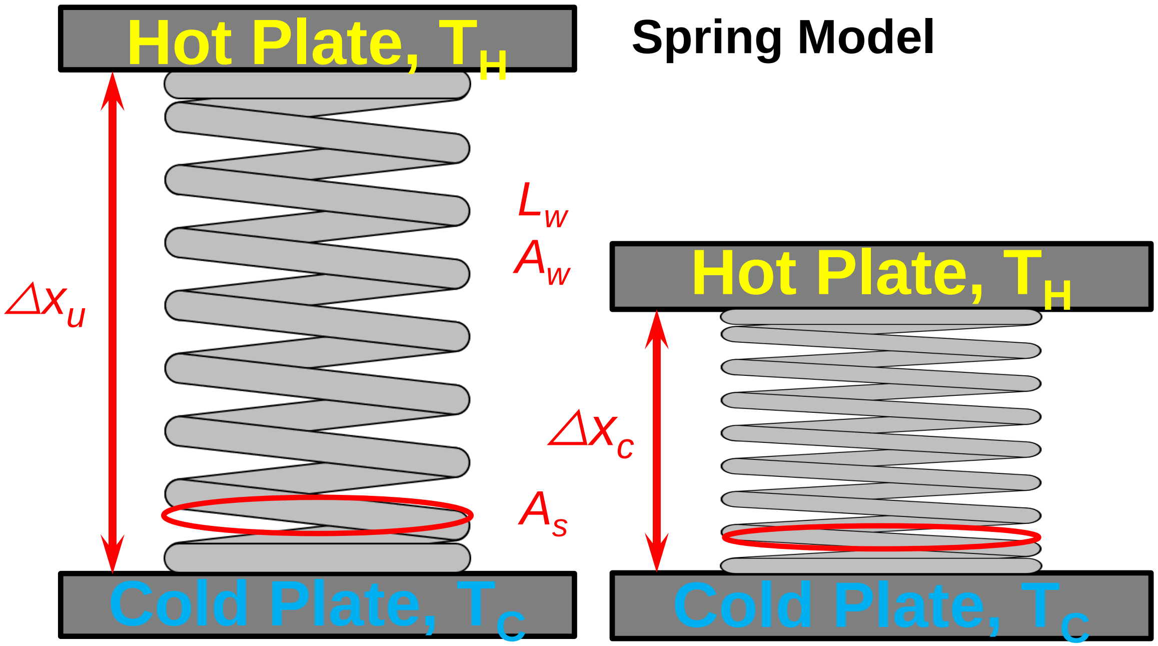
Conductance Ratio

$$r = \frac{G_{Fully-Compressed}}{G_{uncompressed}}$$

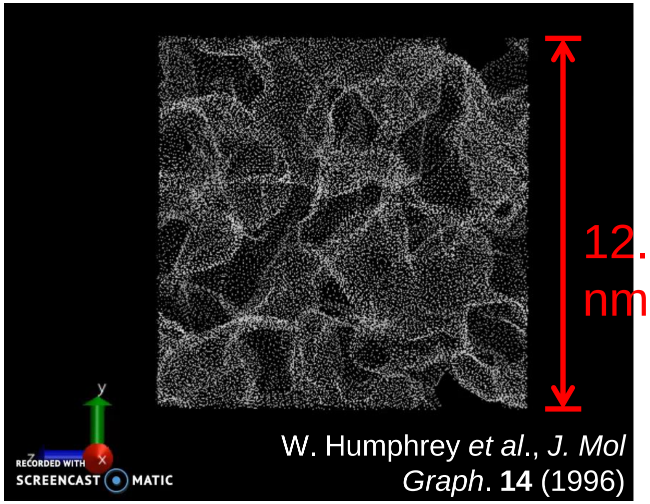
Du *et al.*, *Nat. Comm.*, **12**, 4915 (2021). DOI:10.1038/s41467-021-25083-8

Thermo-Mechanical Modeling

Spring Model



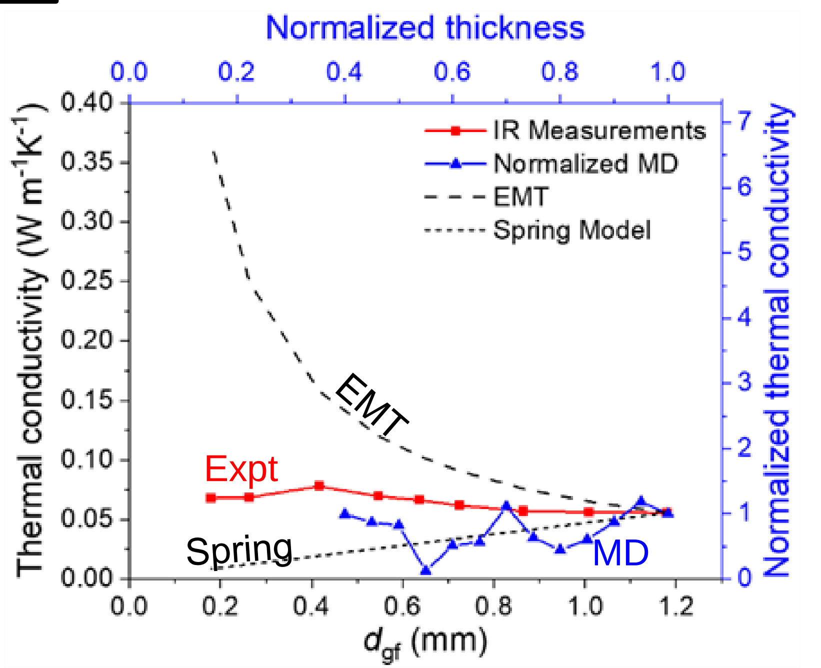
MD Foam Model



$$G_u = \frac{k_u A_s}{x_u} = \frac{k_w A_w}{L_w} = G_c = \frac{k_c A_s}{x_c} = \frac{k_w A_w}{L_w}$$

$$k_c = k_u \frac{x_c}{x_u}$$

How to engineer flexible materials with *k* that significantly increases with decreasing thickness?



Du *et al.*, *Nat. Comm.*, **12**, 4915 (2021).
DOI:10.1038/s41467-021-25083-8

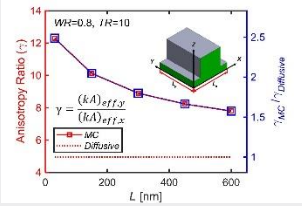
Research Program Overview

Overarching Research Approach:

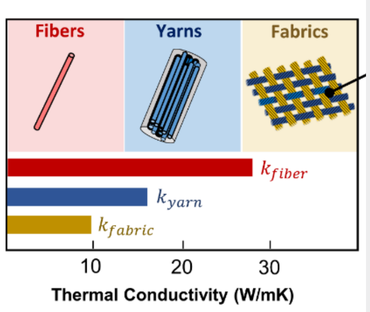
- **Novel experimental metrology tools**
- **Multi-scale computational modeling**
- **Strategic, physics-based design and development of materials & systems**

Transport Phenomena in Multi-scale, Heterogeneous Materials

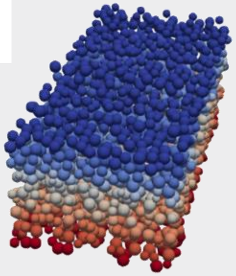
Fundamental Transport Physics



Thermally Conductive Flexible Fibers & Fabrics



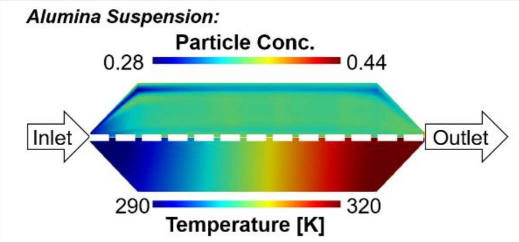
Particulate Materials & Composites

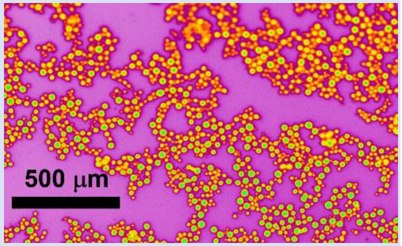


Thermofluids Interactions

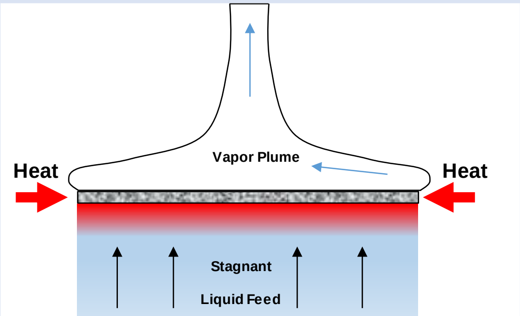
Flow in Dense Suspensions

Collaboration w/ Ivan Christov



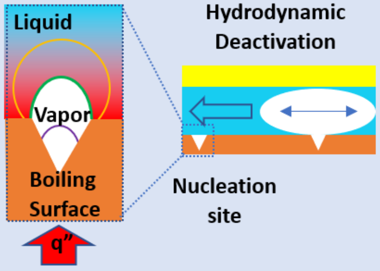


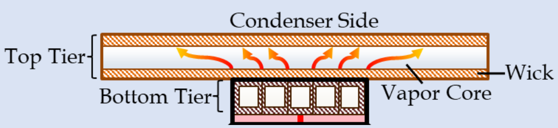
Low Energy Desalination



Alsaati and Marconnet, *Desalination*, 2018.

Confined Boiling



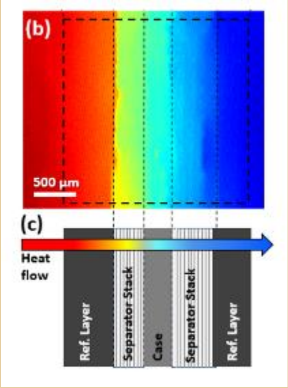


Advanced Vapor Chambers

Collaboration w/ Weibel

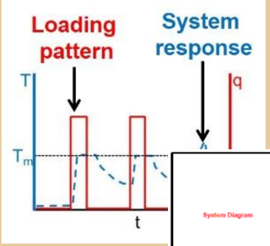
Thermal and Energy Conversion Systems

Batteries Properties & Performance

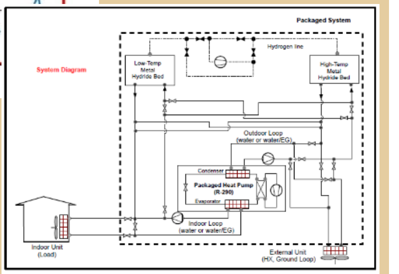


Gaitonde *et al.*, *J. Power Sources*, 2017

Energy Storage Systems Beyond Steady State Cooling



Thermal Storage in HVAC



Summary

Move and Spread The Heat

Advanced Packaging Materials

Fabrics with thermal conductivity of metals and flexibility of polymers

New Metrology Tools

Measure thermal transport (thermal conductivity and interface resistances) for new materials for advanced packaging

Store and Control the Heat

Passive Thermal Management with Phase Change Materials

Energy storage with PCMs can reduce temperatures and temperature oscillations during transient operation of a device

Thermal Switches

Transient thermal management can be aided with active control of heat transfer pathways

Other Potential Areas of Mutual Interest:

- Thermal management of batteries
- Inverse algorithms for hot spot detection with limited temperature sensors
- Two-phase flow and boiling in confined geometries
- Metrology development and materials development/characterization
- …

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Engineering Materials for Thermal Challenges

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