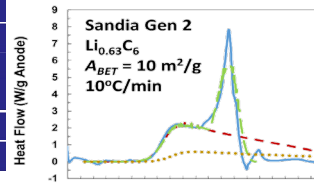
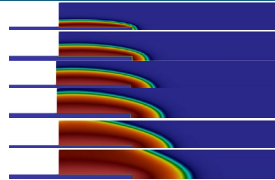
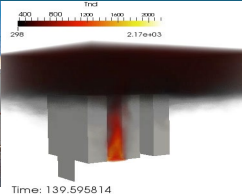
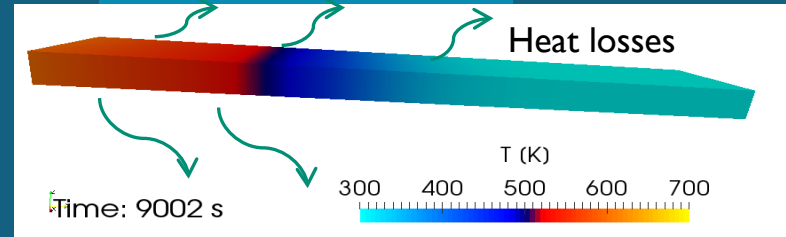




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Slowing and Mitigating Thermal Runaway: A Heat Transfer Perspective



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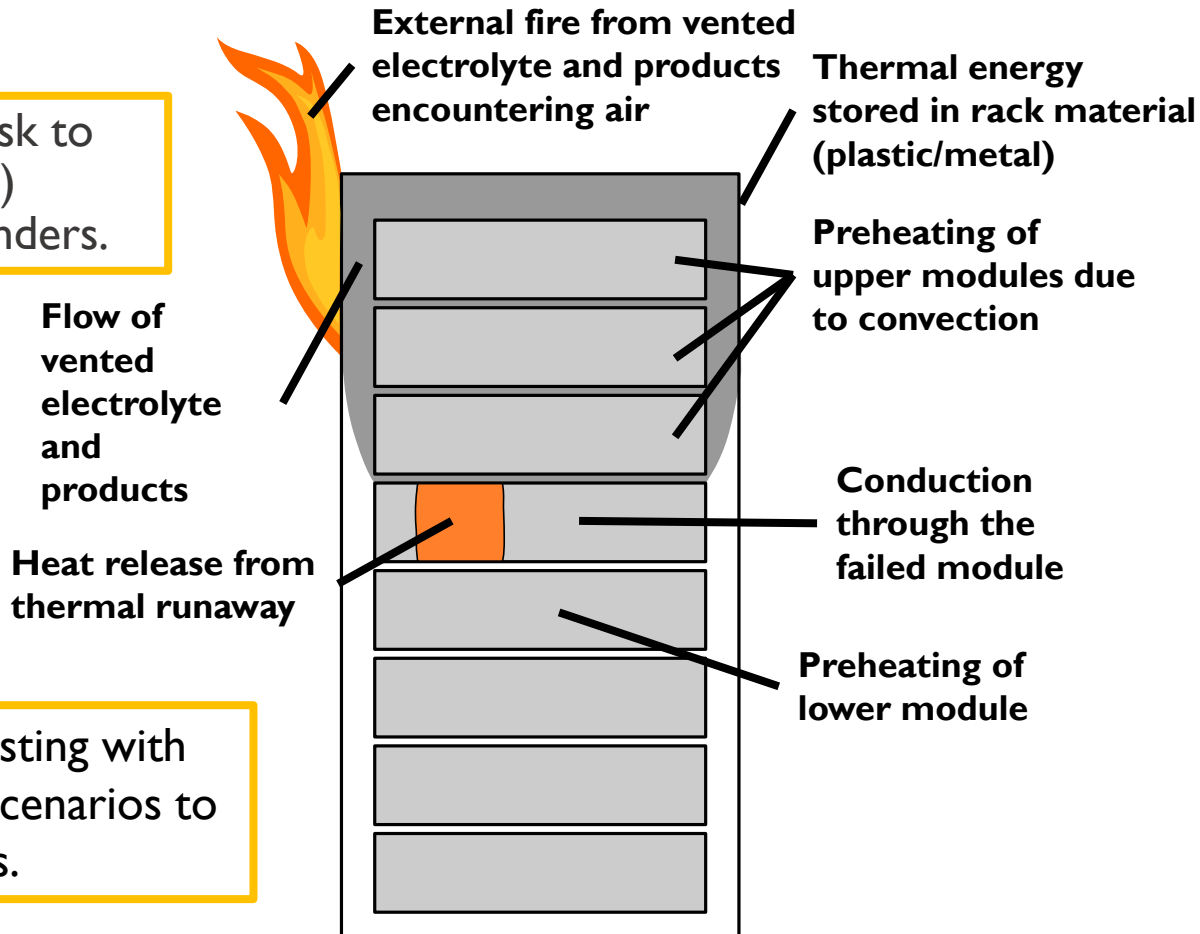


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2 Thermal runaway and energy flows



Cascading failure poses a risk to energy storage system (ESS) installations and first responders.



We want to supplement testing with predictions of challenging scenarios to inform mitigation strategies.

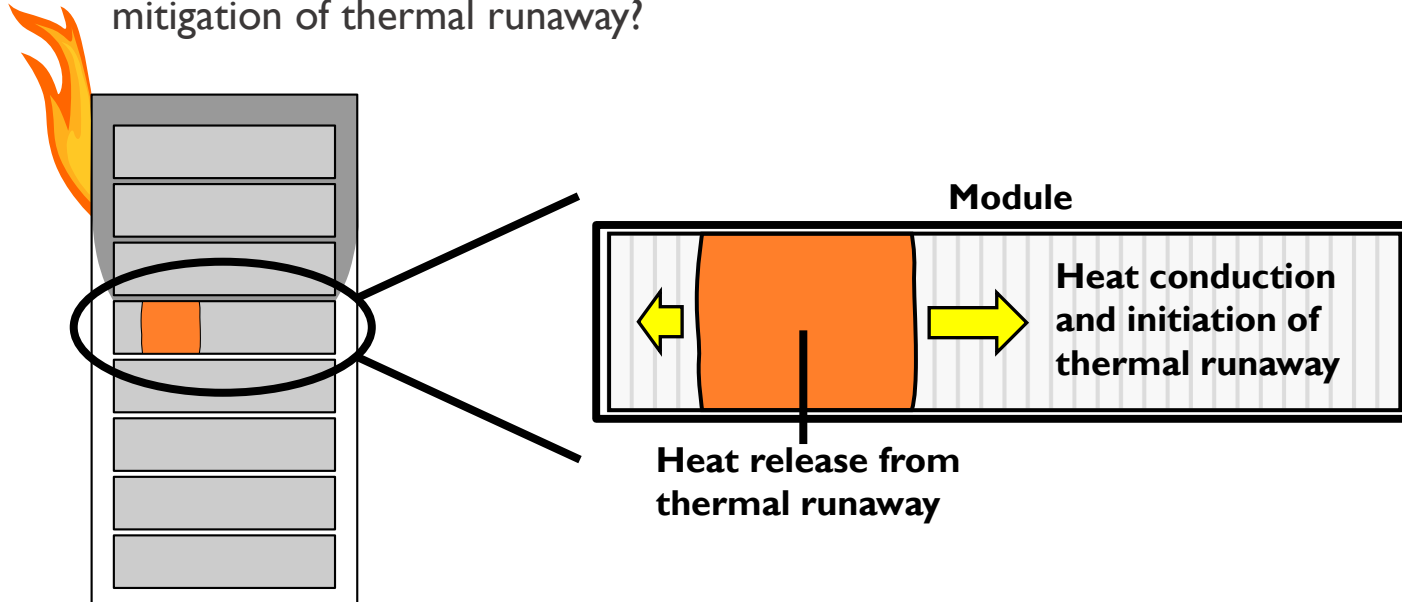
The boundary between propagation and mitigation



Examining the energy flows in an ESS, cascading failure at the module level is the primary source of energy (produces flaming gases, ignites plastics).

How do the relative time scales of these flows affect the propagation rate?

How do the properties of the system impact the boundary between propagation and mitigation of thermal runaway?



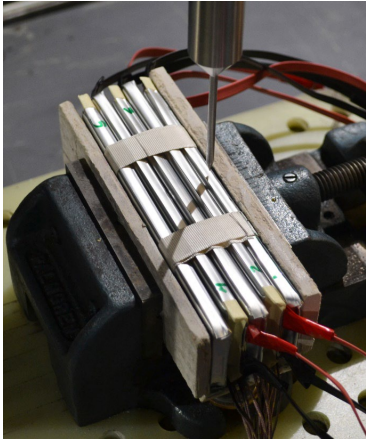
Cascading failure predictions at the module scale



Nail penetration test in a stack of 5 lithium cobalt oxide pouch cells (3Ah).

- Experiments from Torres-Castro et al. 2020.
- Simulations from open source software Lithium-ion Modeling with I-D Thermal Runaway (LIMITR) <https://github.com/ajkur/limitr>

Top Perspective View



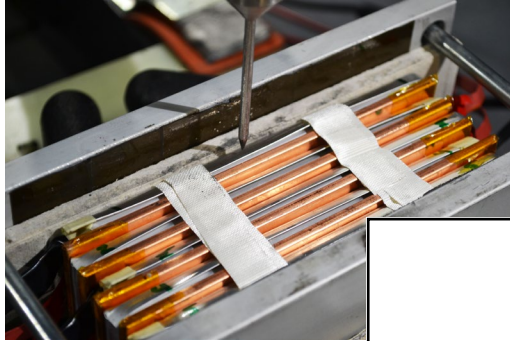
The
Locations



Mitigation of cascading failure at the module scale: 5 cell stack with 1/8" copper spacers



Top Perspective View



Adding thermal mass of the copper plates mitigates cascading failure.

Torres-Castro, L. et al., (2020) J Electrochem. Soc., **167**(9): 090515

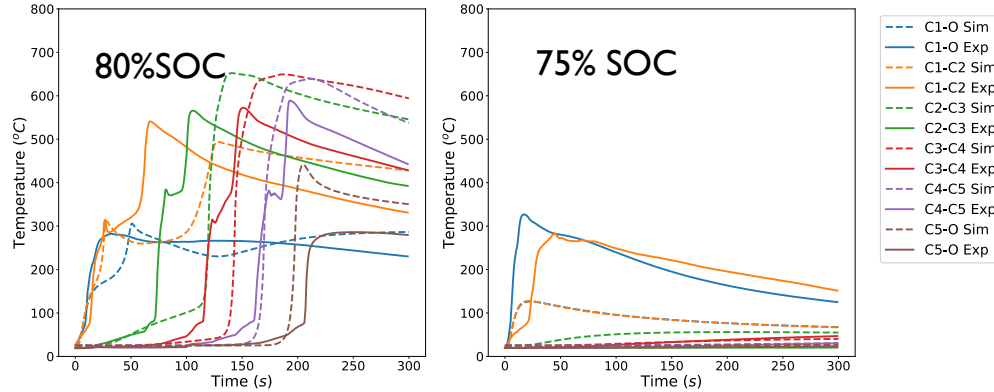
Kurzwski, A., et al. (2020). Proc. Combust. Instit. **38**.



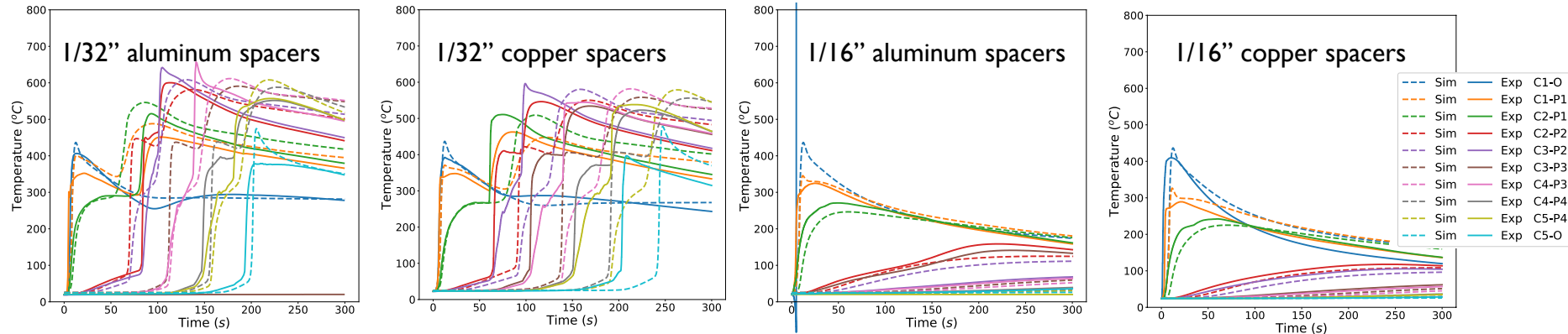
New chemistry models successfully predict full range of scenarios



Temperature-time propagation measurements and predictions



- Successful prediction over a range of reduced SOC and metallic inserts.
- Collectively add heat capacity & increase time delay for cell runaway.
- Prevent propagation for 30% increase in net heat capacity.



Simplified scenario and reduced parameter set for mitigation

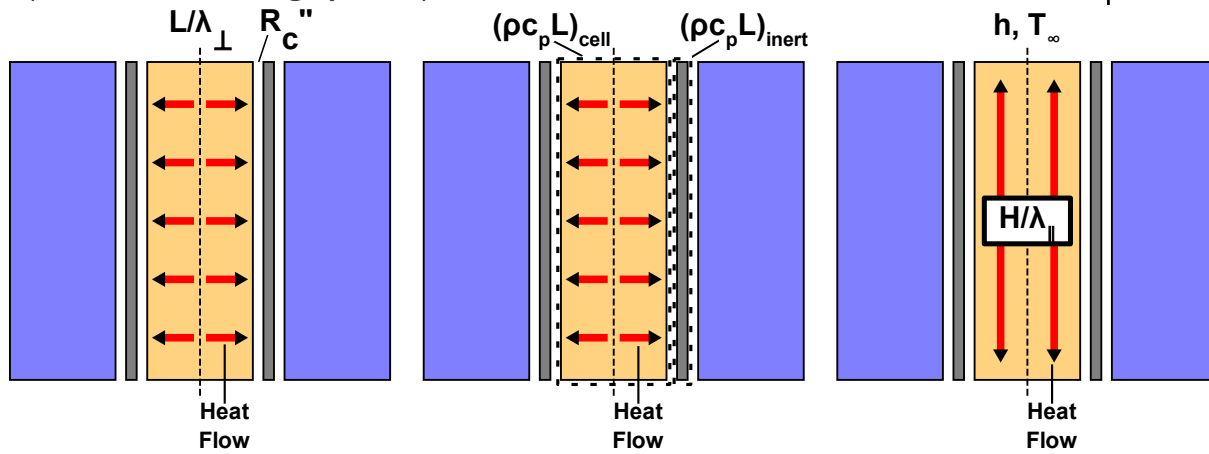
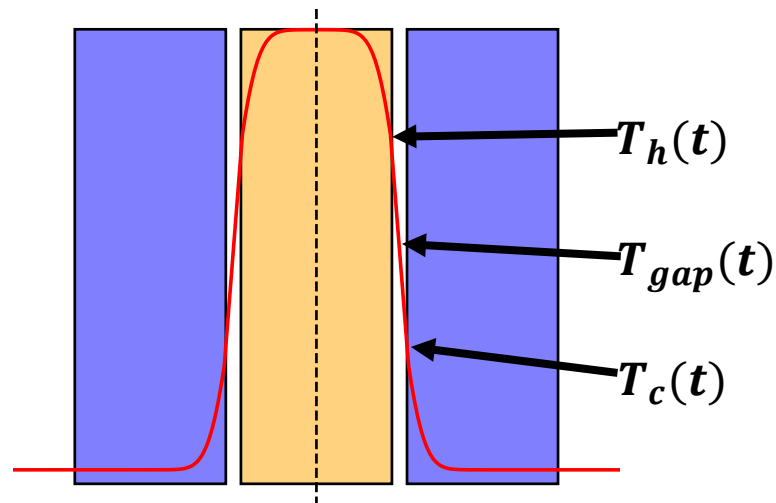


What is a low-dimensional parameter space that affects the propagation/mitigation boundary?

Seek to dissipate heat to avoid/slow down propagation.

Parameters affecting target cell temperature:

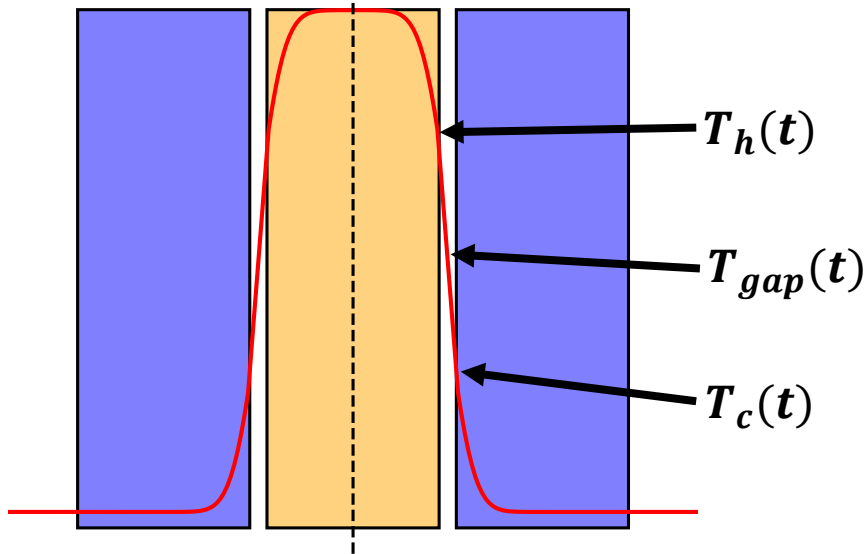
- Thermal resistance along the stack.
- Ability to dissipate heat.
- Heat sinks (structure/cooling system).



Simplified scenario: heat transfer along an adiabatic stack

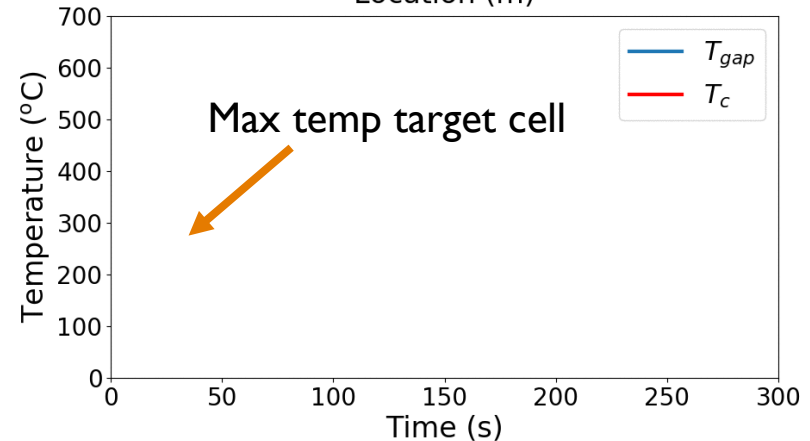
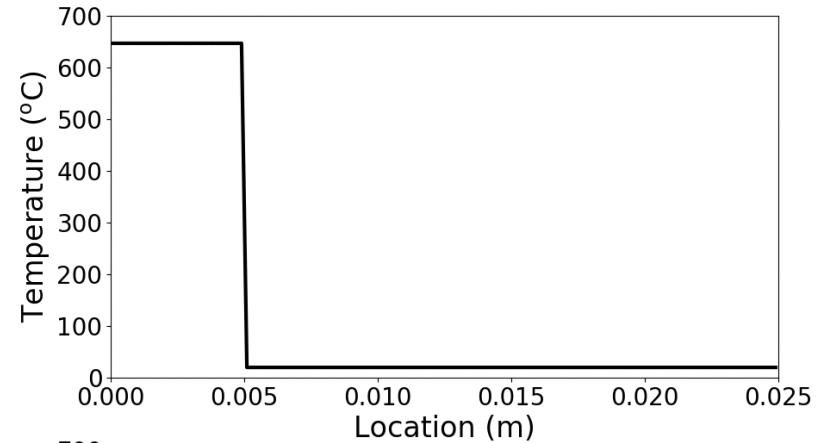


Initiating Cell
Target Cell



Three models:

- Analytical composite slab: 1-D, no external convection
- LIMITR: quasi-1-D, external convection
- Aria: 3-D



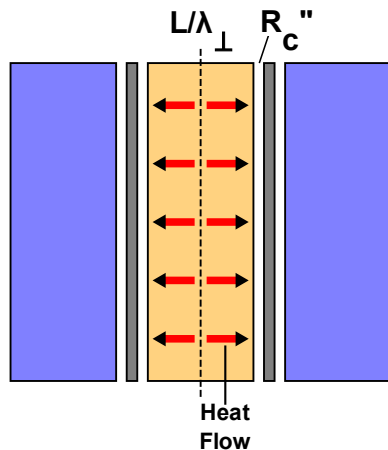
Characteristic heat transfer: conduction and capacitance



Resistance Ratio

Thermal resistance between cells is characterized by contact resistance and inert material resistance:

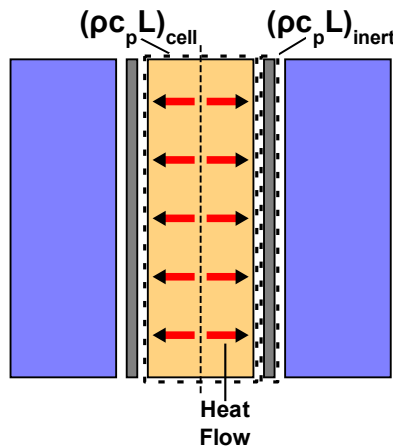
$$\frac{1}{Bi} = \frac{R''_{contact} + (\delta/\lambda)_{inert}}{(L/\lambda)_{cell}}$$



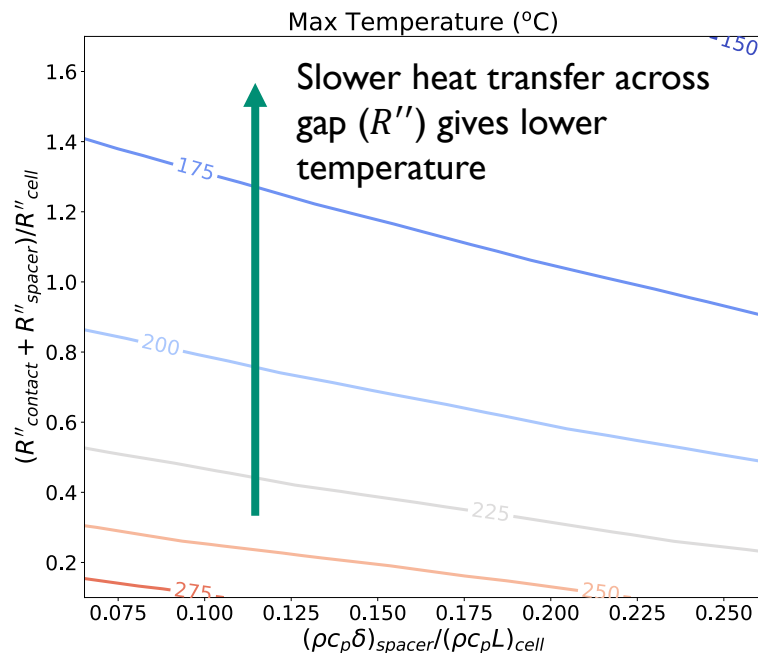
Capacity Ratio

The heat capacity ratio of inert spacer material to cells is:

$$\phi_{capacity} = \frac{(\rho c_p \delta)_{inert}}{(\rho c_p L)_{cell}}$$



Max temperature of target cell ($T_{c,max}$)

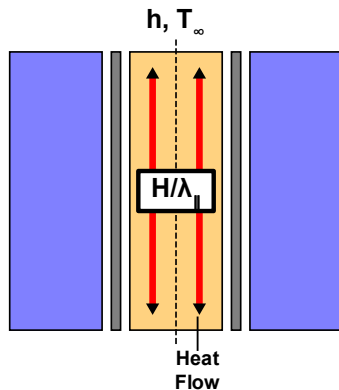
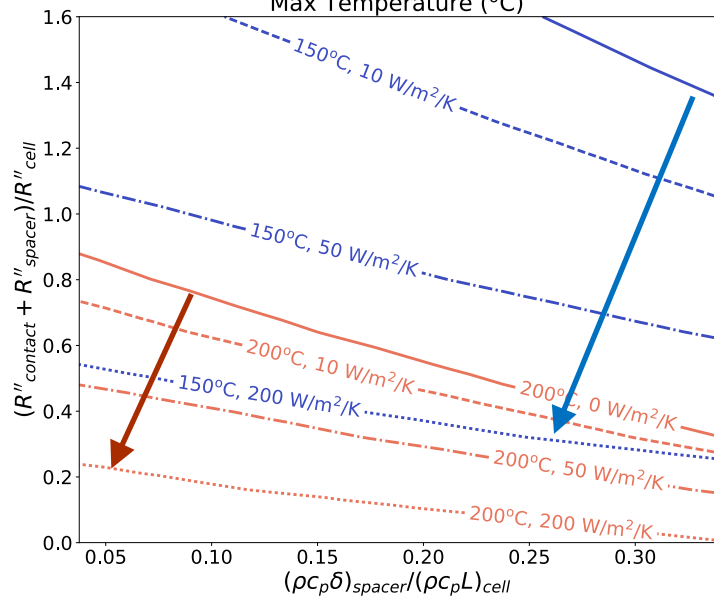


Map of limiting temperature vs. thermal resistance, capacity, and cooling



Max temp of target
cell with cooling

Max Temperature (°C)

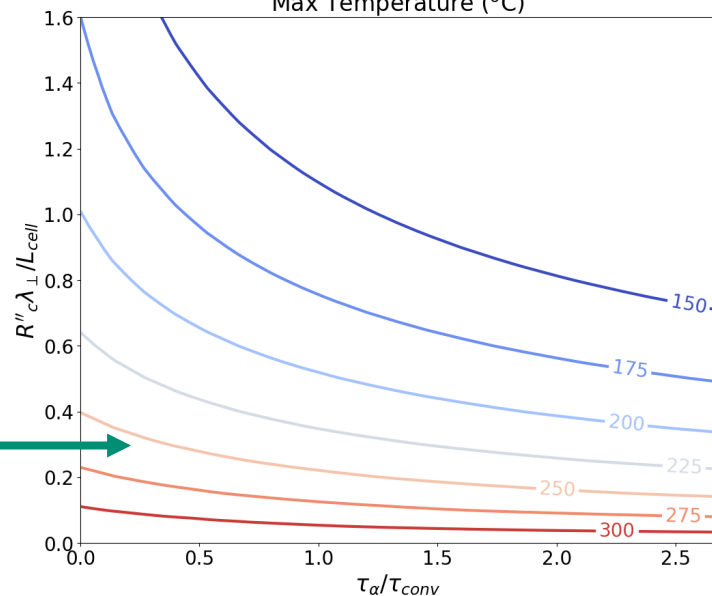


In the $\phi_{\text{capacity}} = 0$
limit, timescale ratio
collapses temperatures

Time Scale Ratio

$$\psi = \frac{\tau_{\alpha}}{\tau_{\text{conv}}} = \frac{L_{\text{cell}}^2/\alpha}{\rho V c_p / h_{\infty} A_{\text{ext}}}$$

Max Temperature (°C)





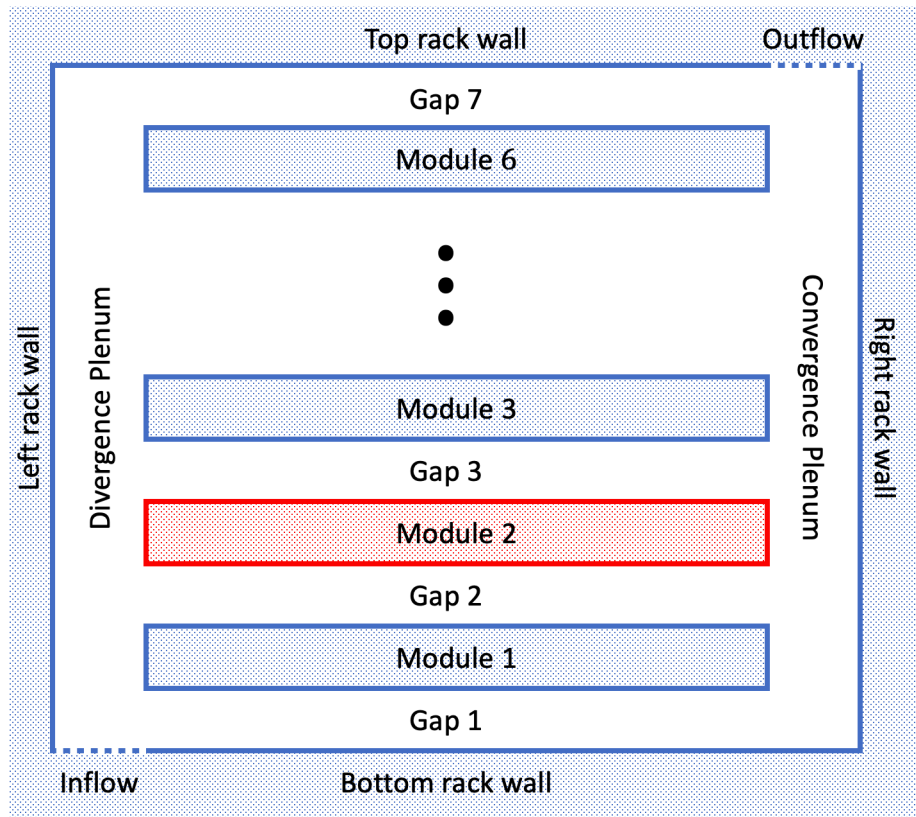
Need to characterize module-to-module heat transfer to develop low fidelity models and efficiently explore the parameter space.

Which parameters have the greatest effect on conductances?

- Inflow/outflow BCs
- Gap between modules
- Module temperatures

Begin with simplified 2-D model to understand flow and heat transfer.

- Heat transfer between modules and air
- Flow rate and drag through gaps
- Buoyancy-driven heated air
- Relevant non-dimensional parameters: Rayleigh number, Richardson number, etc

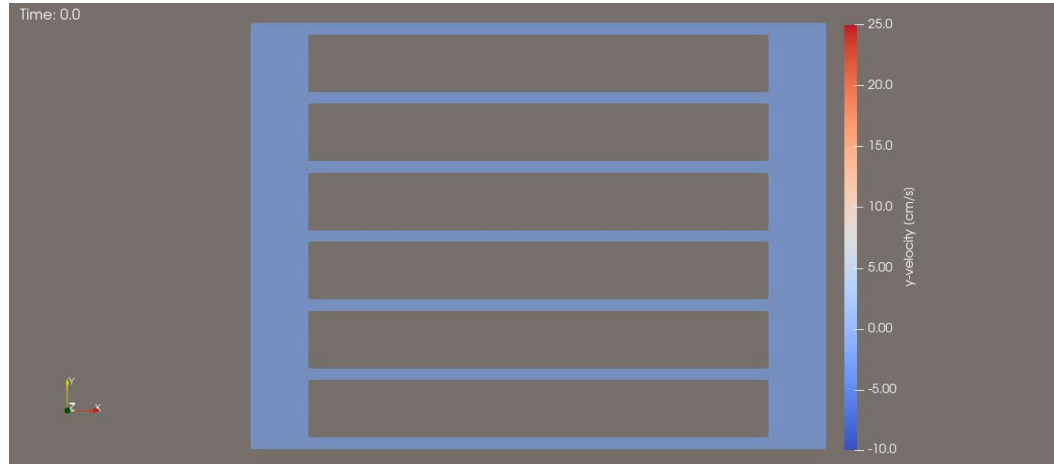




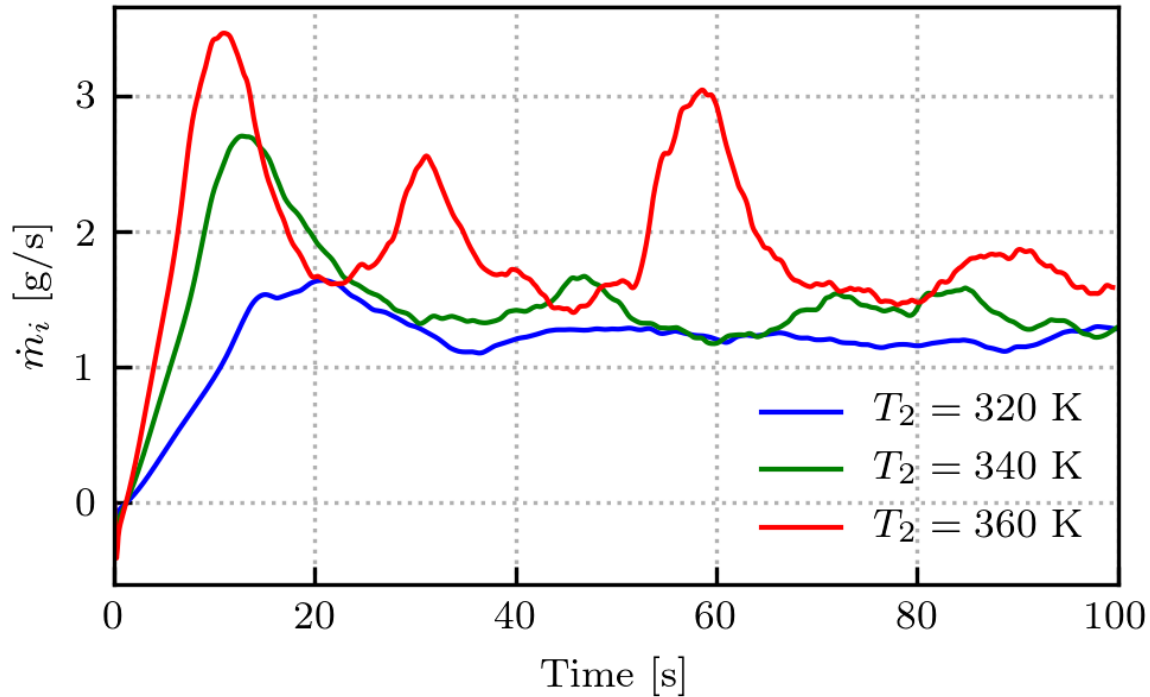
Temperature



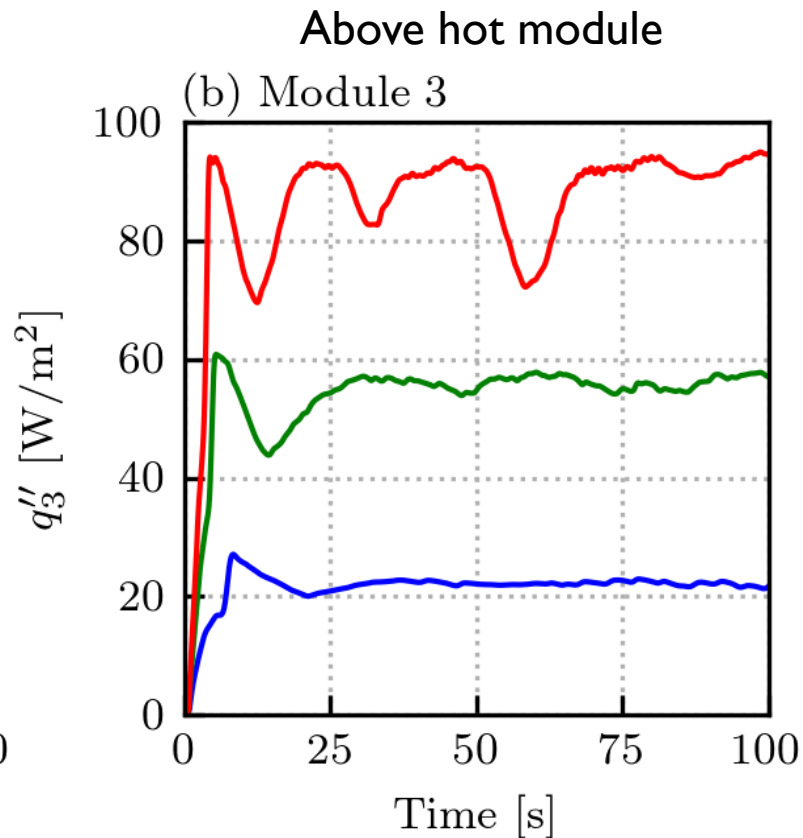
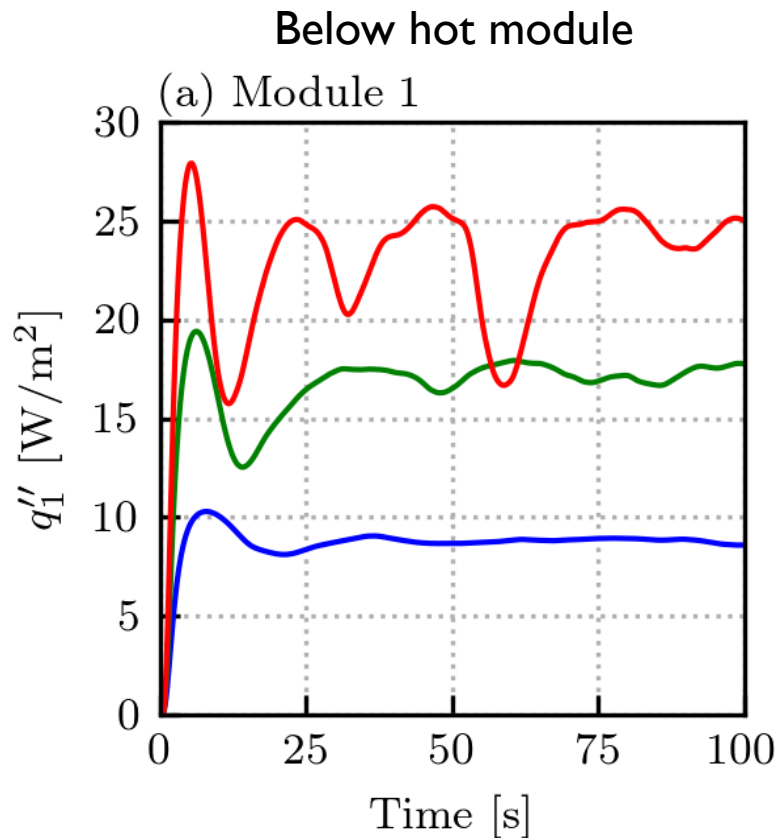
**Vertical (y)
Velocity**



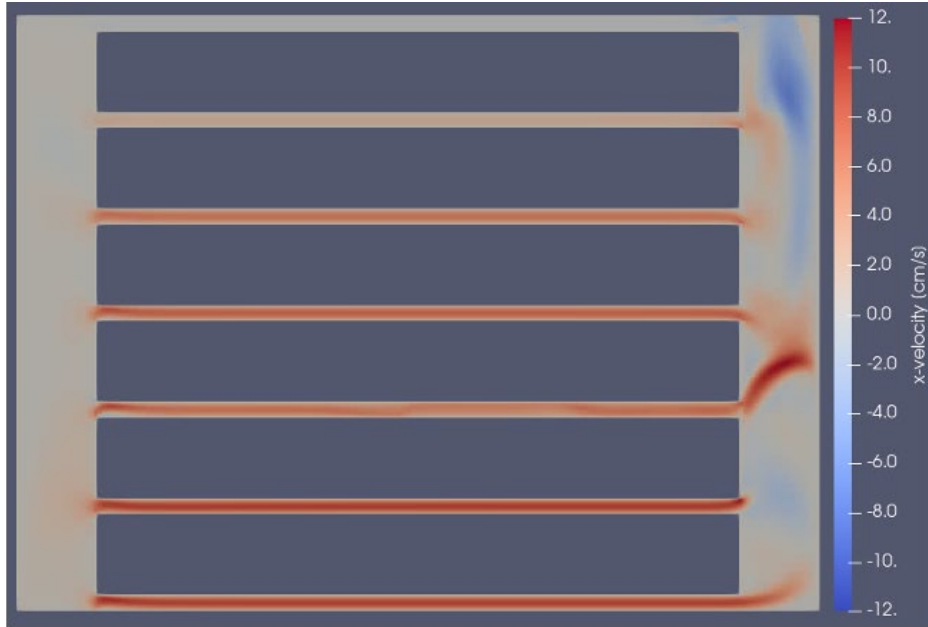
Effect of module temperature on mass flow through the system



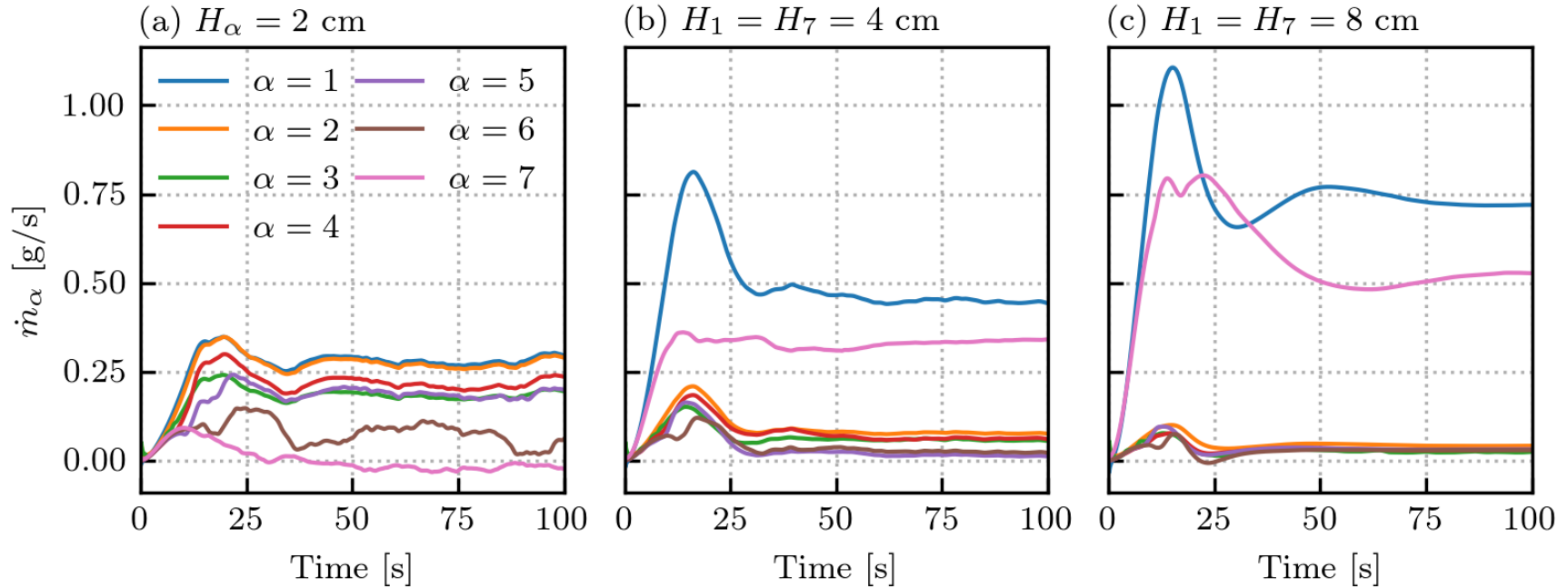
Effect of module temperature on heat flux to neighboring modules



Effect of gap size on mass flow through each gap



Effect of gap size on mass flow through each gap



Note: α = gap index starting from the lowest gap

We need to develop low fidelity network models that capture the essential heat transfer characteristics to explore parameter space

Detailed numerical simulations:

$$\frac{\partial \rho}{\partial t} = \dots, \frac{\partial T}{\partial t} = \dots, \frac{\partial u_i}{\partial t} = \dots$$

Expensive – millions of CPU hours

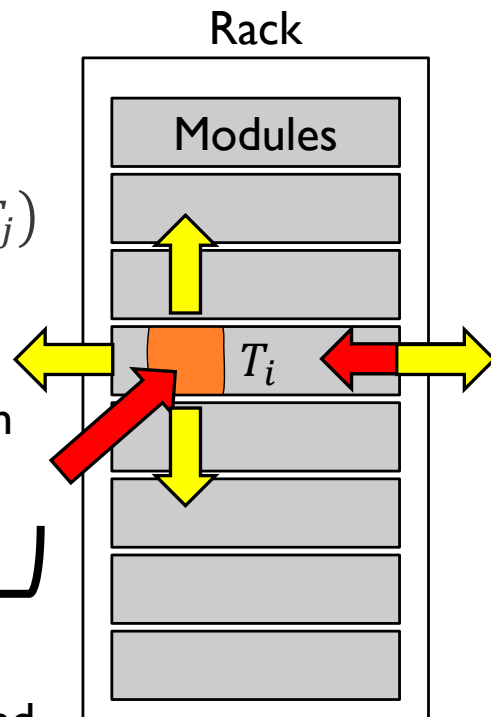
Network model:

$$M_i c_p \frac{dT_i}{dt} = P_i(t) - \sum_{j=1}^N \theta_{i,j} (T_i - T_j)$$

Heat
Generation

Transfer Between
Modules

Inexpensive – less than one second



Summary

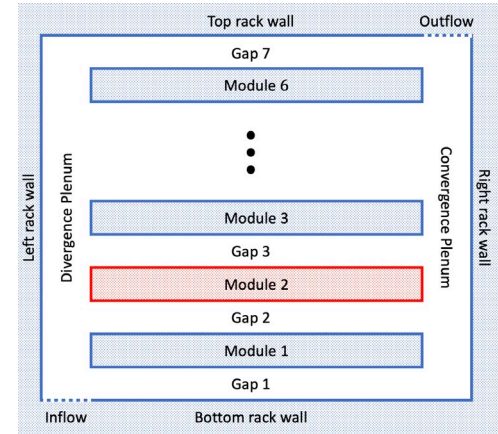
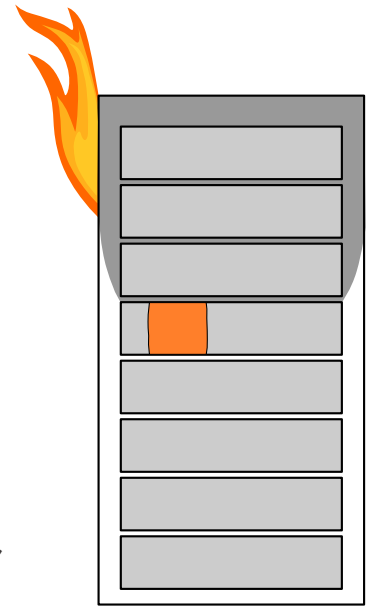
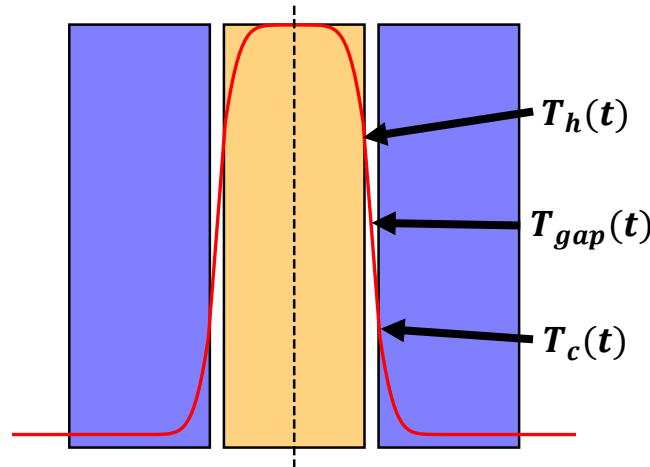
Understanding of heat transfer scales is critical for system design and safety.

Non-dimensional parameters can be used to describe heat flows at the module scale.

Began characterization of heat flows at the rack scale

- See poster “Flow dynamics through simplified battery rack configurations” for more details

Predictive, low-order models are needed to explore the vast parameter space.



Acknowledgment



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