

Experimental and Modeling Study of Thermal Runaway Propagation of 18650 Form-factor Lithium-ion Battery Array

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Problem – Data Center Lithium-ion Battery Backup Unit



- Distributed energy storage in large data center



Problem – Data Center Lithium-ion Battery Backup Unit

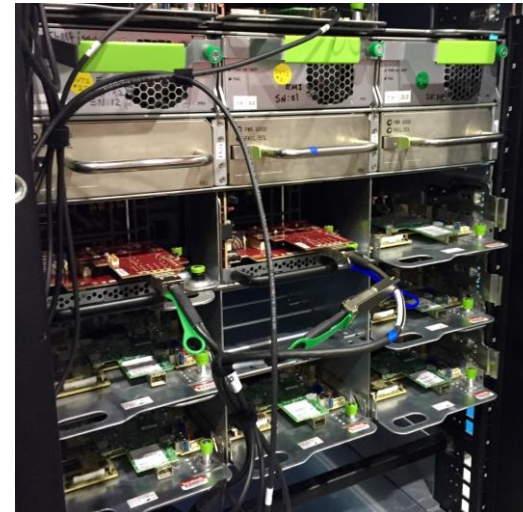
- Potential hazards
 - Fire propagation
 - Corrosive gas
- Engineering evaluation
 - Thermal runaway propagation rate
 - Generation rate of gas



18650 Cell



BBU module



Server system

Cell level



- ☒ Cell level thermal runaway test
- ☒ Cell thermal runaway model

Previous work



Module level



- ☐ Simplified module design and heat transfer analysis
- ☐ Thermal runaway propagation model

Current work



System level

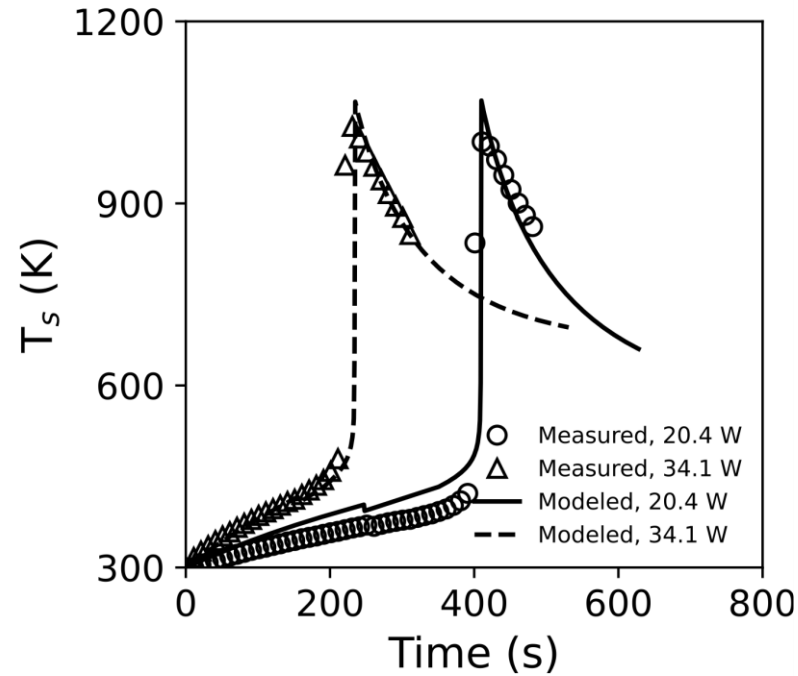
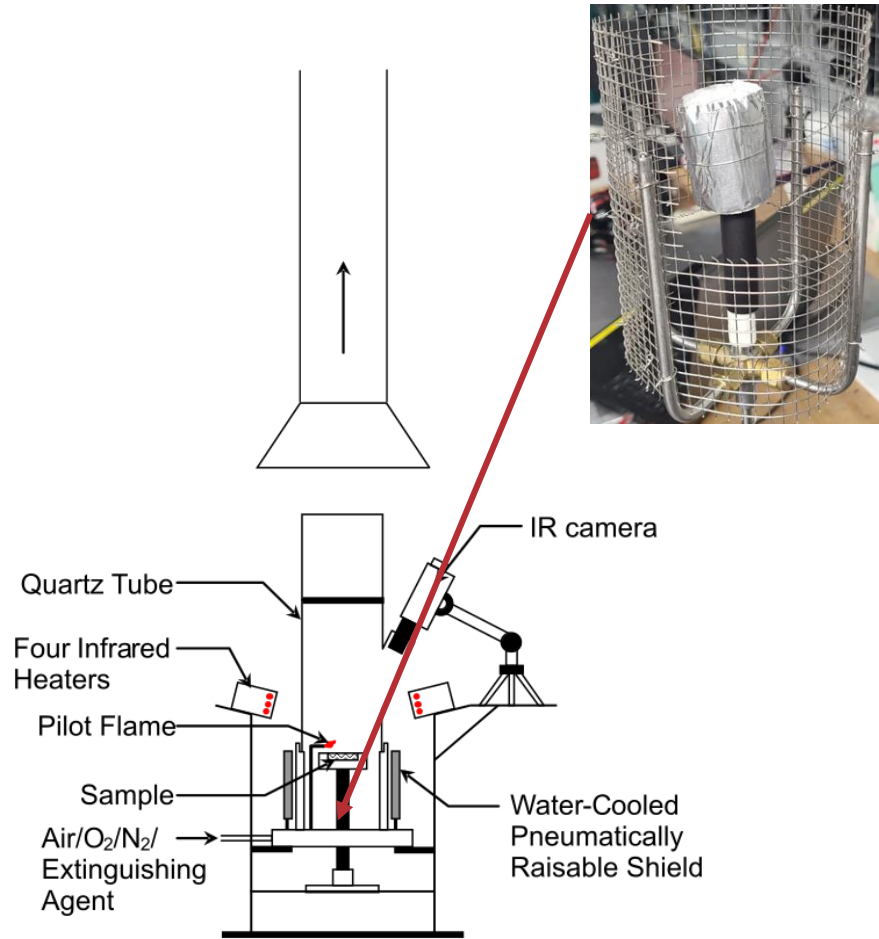


- ☐ Module-to-module fire spread
- ☐ CFD (FireFOAM) modeling

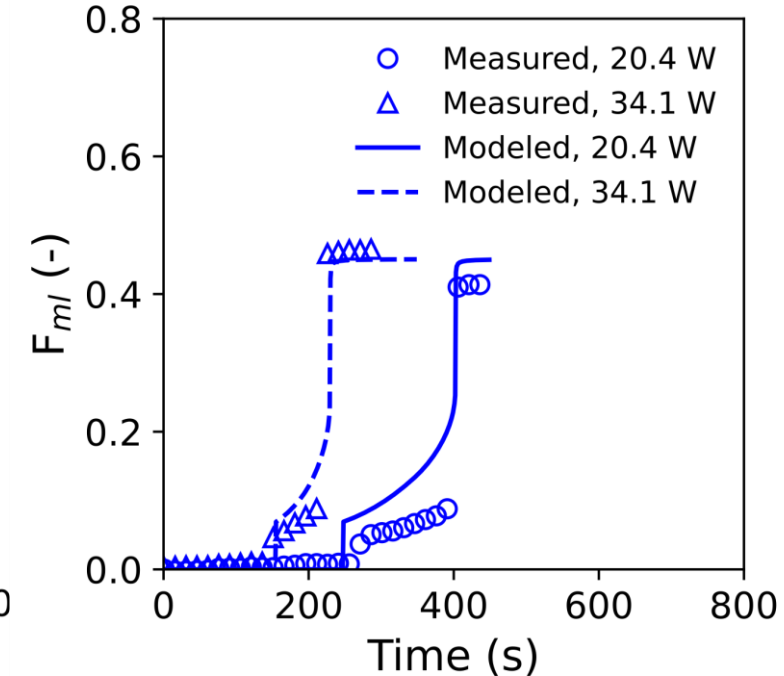
Future work



Previous Work – Lumped Cell Thermal Runaway Model



Surface temperature



Mass loss fraction



Previous Work – Lumped Cell Thermal Runaway Model

Chemical reactions and rates:

$$v_l \rightarrow g; \dot{\omega}_l = -(m_l/m_{l0})^{n_l} m_{l0} A_l e^{-E_l/(RT)}$$

$$v_h \rightarrow c + g; \dot{\omega}_h = -(m_h/m_{h0})^{n_h} m_{h0} A_h e^{-E_h/(RT)}$$

$$\dot{Q}_{ISC} = \eta_{ISC} \text{cond} H_{ISC} \cdot A_{ec} e^{-E_{ec}/k_b T}$$

Energy conservation:

$$\frac{dU_{cv}}{dt} = \dot{Q}_{ext} - \dot{Q}_l + \dot{Q}_{IHG} - \dot{m}_{vent} h_{vent}$$

$$\dot{Q}_{IHG} = \dot{\omega}_l \Delta U_l + \dot{\omega}_h \Delta U_h + \dot{Q}_{ISC}$$

Mass conservation:

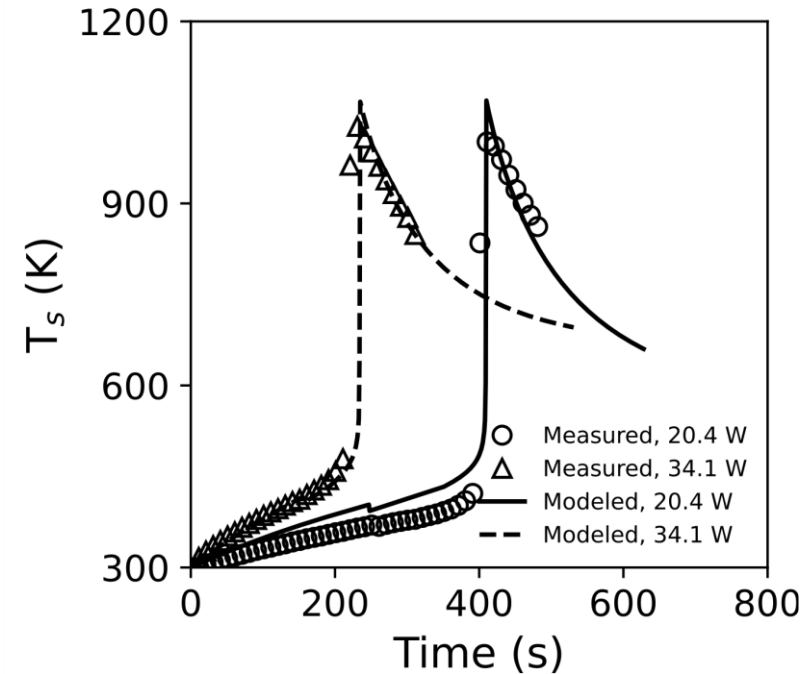
$$m_{cv} = m_s + m_g$$

$$\dot{m}_{cv} = \dot{m}_{vent}$$

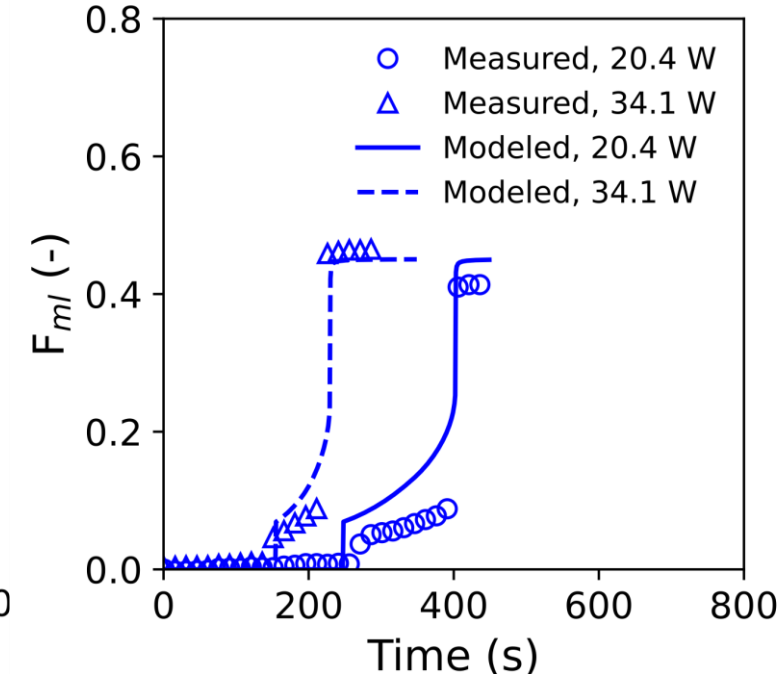
Species conservation:

$$\dot{m}_s = \dot{\omega}_s = \dot{\omega}_l + \dot{\omega}_h$$

$$\dot{m}_g = -\dot{\omega}_s - \dot{m}_{vent}$$



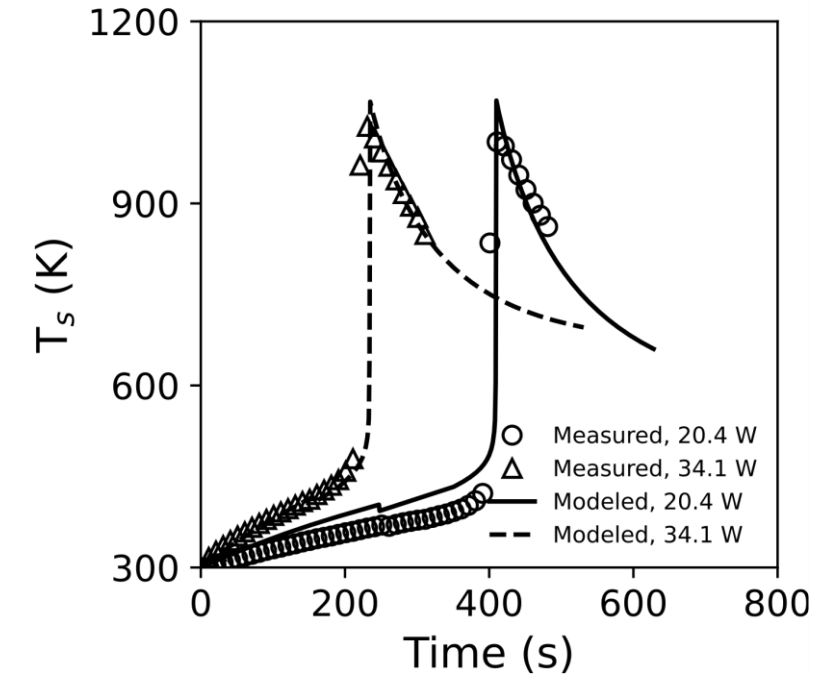
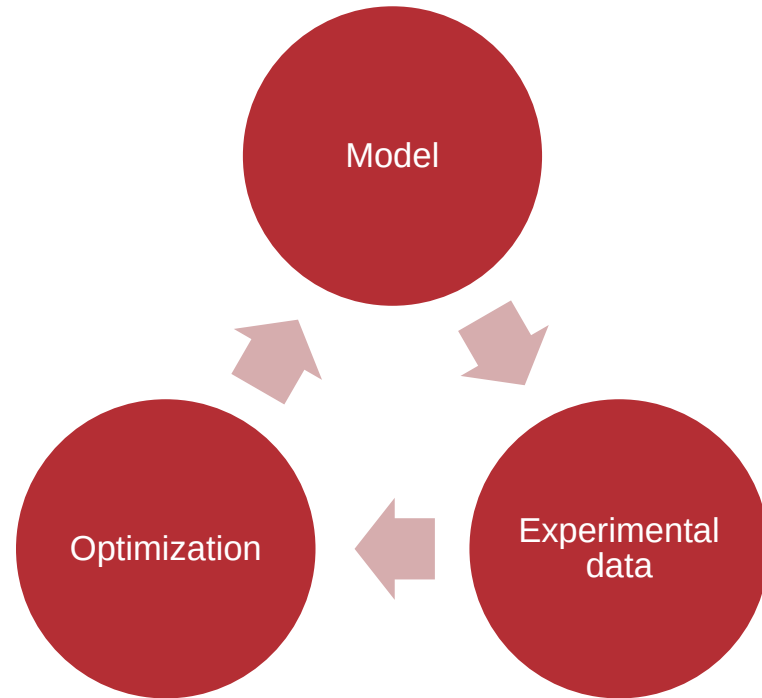
Surface
temperature



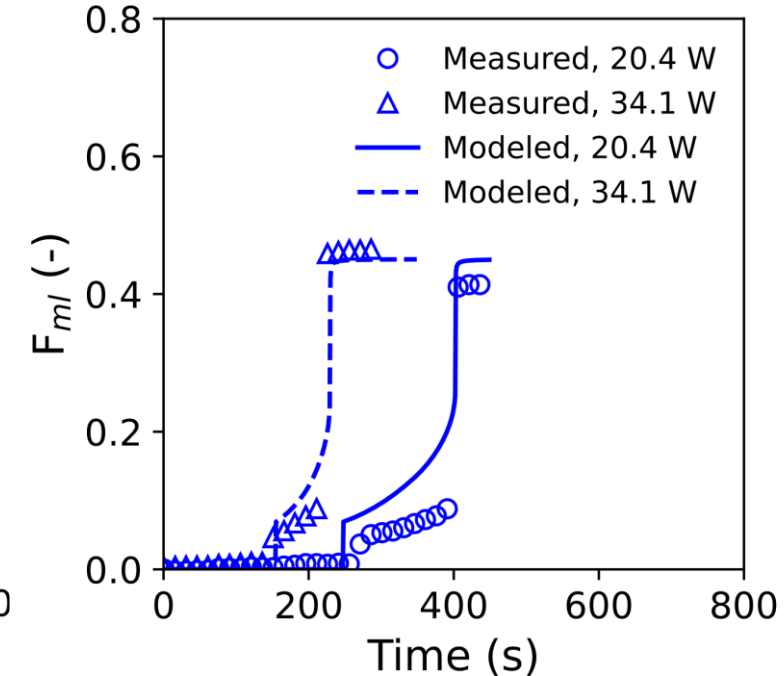
Mass loss fraction



Previous Work – Lumped Cell Thermal Runaway Model



Surface temperature

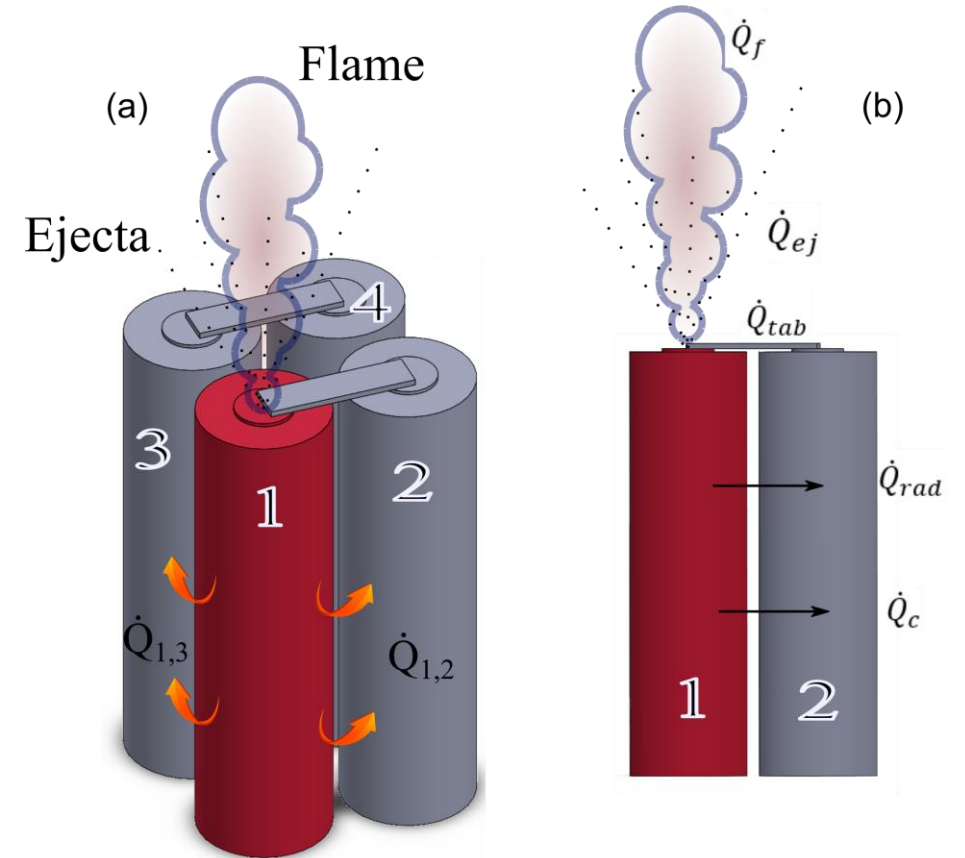


Mass loss fraction



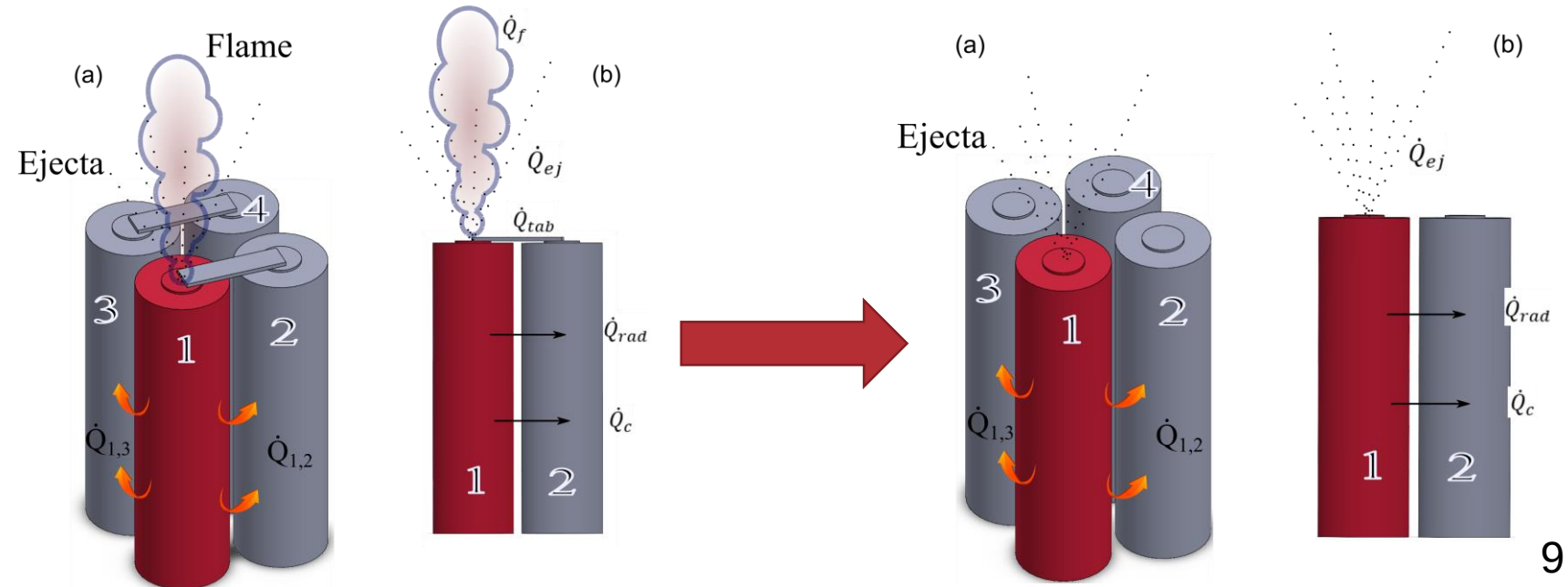
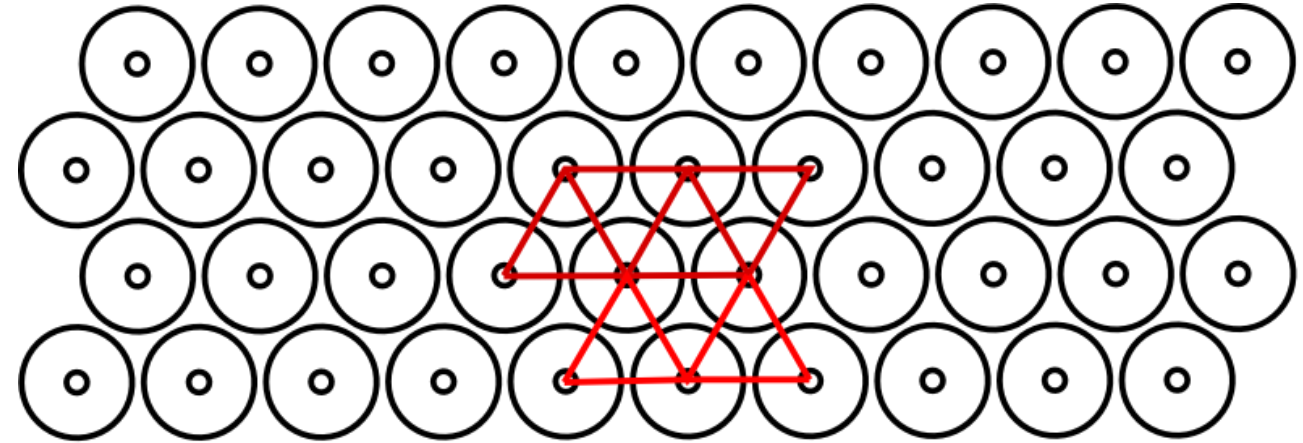
Thermal Runaway Propagation (TRP) Model

Fire spread		Thermal runaway propagation	
Time to ignition	→	Time to thermal runaway event	
Flame preheating	→	Cell to cell heat transfer	



Thermal Runaway Propagation – Network Modeling

- Network concept
 - Each cell is a lumped node
 - Cell is modeled by cell-level thermal runaway model
 - Cell to cell heat transfer

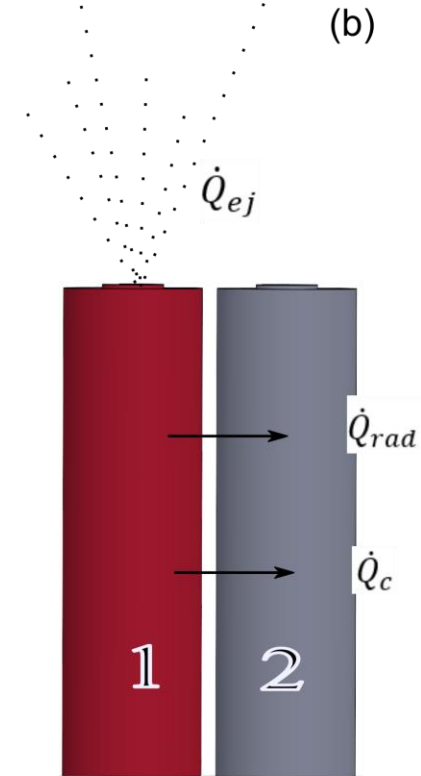
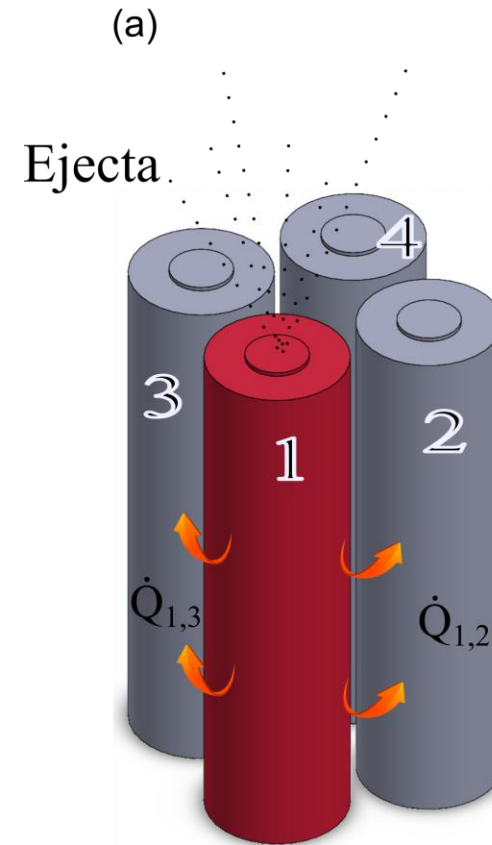


TRP Model

Mass conservation:

$$m_i = \underbrace{m_{i,s} + m_{i,g}}_{\text{Species inside cell}} + \underbrace{\sum_{j \neq i} F_{ji} m_{j,ej}}_{\text{Ejected solids from cell \#j to \#i}} m_{solid}$$

$$\dot{m}_i = \dot{m}_{i,vent} + \sum_{j \neq i} F_{ji} \dot{m}_{j,ej}$$



TRP Model

Energy conservation:

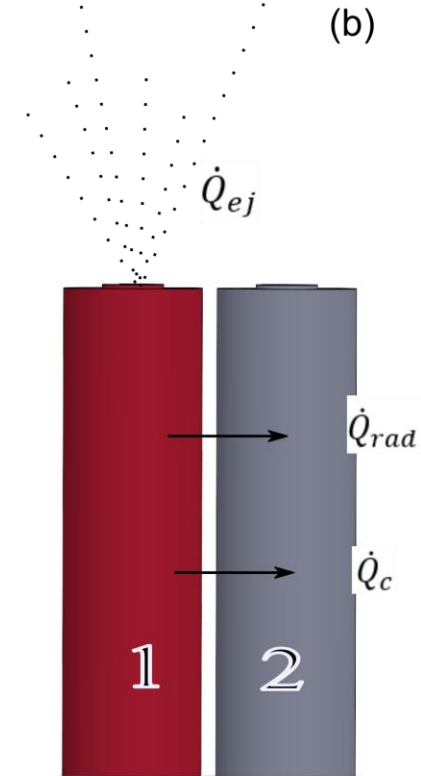
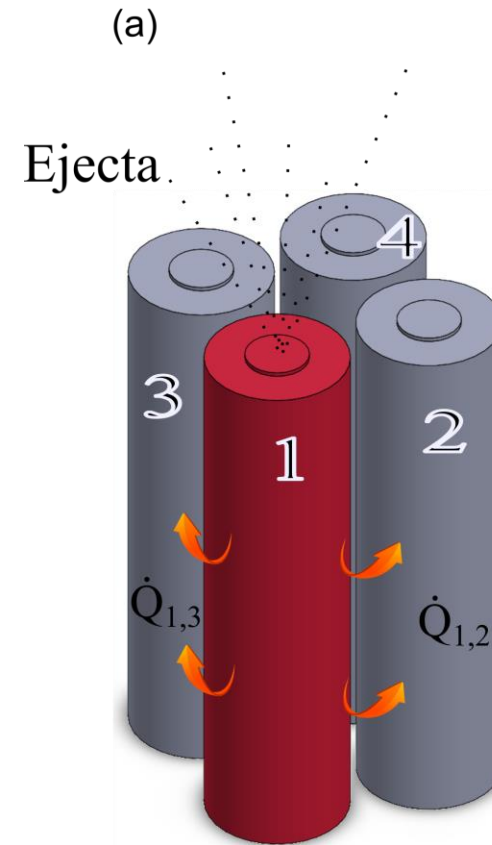
$$\frac{dU_i}{dt} = \underbrace{\dot{Q}_{i,IHG} - \dot{m}_{i,vent} h_{vent}}_{\text{Cell-level model}} + \sum \dot{Q}_{i,s} + \underbrace{\sum_{j \neq i} F_{ji} [\dot{m}_{j,ej_{solid}} h_{ej} + \dot{m}_{j,ej_{gas}} (h_{ej} - h_{T_i})]}_{\text{Energy transfer from ejecta of cell \#j to \#i}}$$

$$\dot{Q}_{i,s} = -\dot{Q}_{i,l} + \sum_{j \neq i} \underbrace{(\dot{Q}_{j,i,rad} + \dot{Q}_{j,i,con})}_{\text{Radiation and effective conduction between cell bodies}}$$

Mass conservation:

$$\dot{m}_i = \dot{m}_{i,s} + \dot{m}_{i,g} + \sum_{j \neq i} F_{ji} \dot{m}_{j,ej_{solid}}$$

$$\dot{m}_i = \dot{m}_{i,vent} + \sum_{j \neq i} F_{ji} \dot{m}_{j,ej}$$



Heat Transfer Analysis between Cells

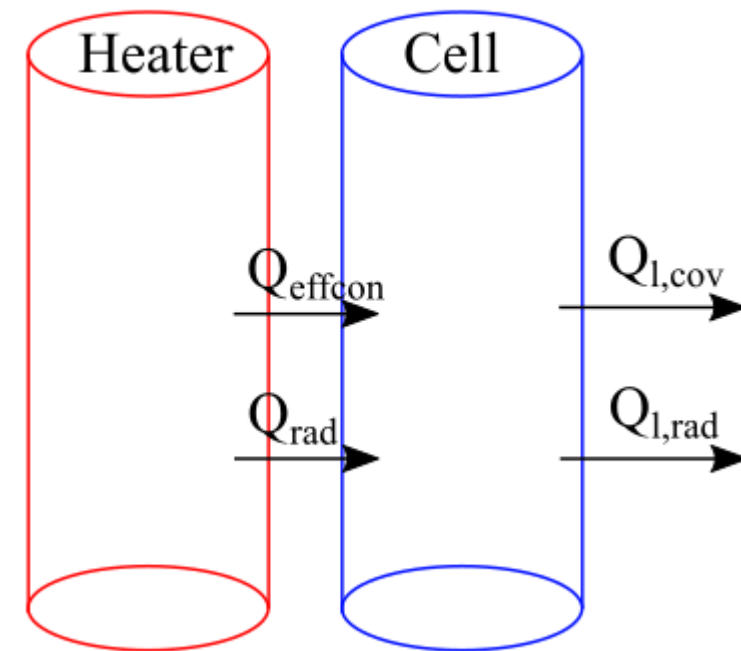
- Copper slug array
- Heat transfer includes radiative and effective conductive heat transfer between cells

$$\dot{Q}_{i,s} = -\dot{Q}_{i,l} + \sum_{j \neq i} (\underbrace{\dot{Q}_{j,i,rad} + \dot{Q}_{j,i,con}})$$

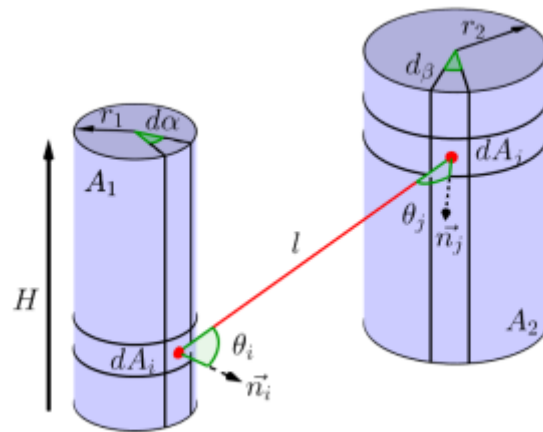
Radiation and effective conduction between cell bodies



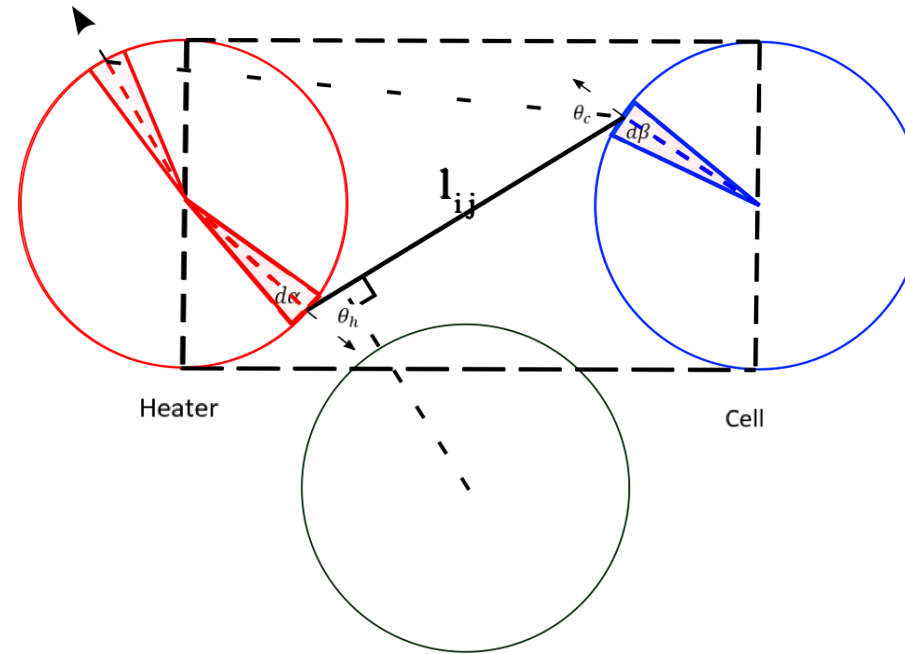
$$\dot{Q}_{rad} + \dot{Q}_{effcon} = m \frac{d(c_p T)}{dt} + \dot{Q}_{lossrad} + \dot{Q}_{lossconv}$$



- View factor calculation
 - Numerical integration
 - Blocking effect



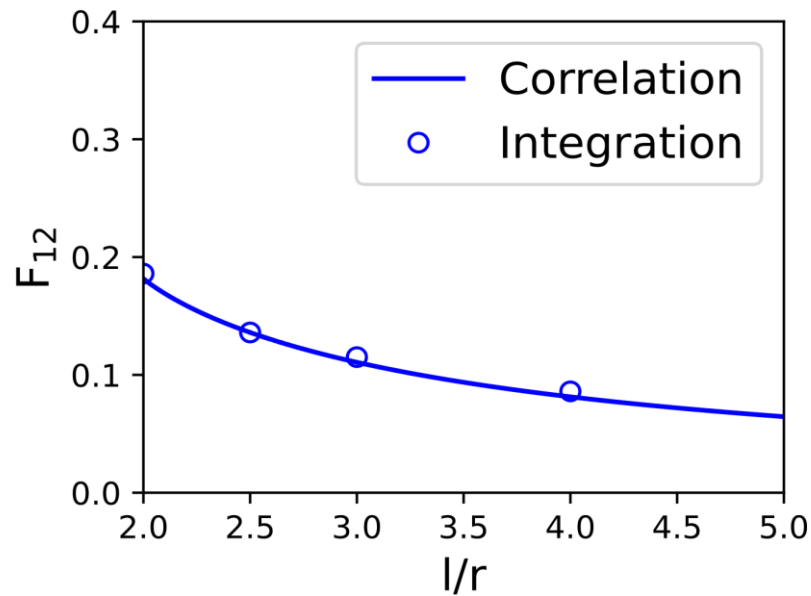
$$\dot{Q}_{rad} = \frac{\sigma(T_h^4 - T_c^4)}{\frac{1 - \varepsilon_h}{A_1 \varepsilon_h} + \frac{1}{A_1 F_{12}} + \frac{1 - \varepsilon_c}{A_2 \varepsilon_c}} = A_1 F_{12} \sigma(T_h^4 - T_c^4)$$



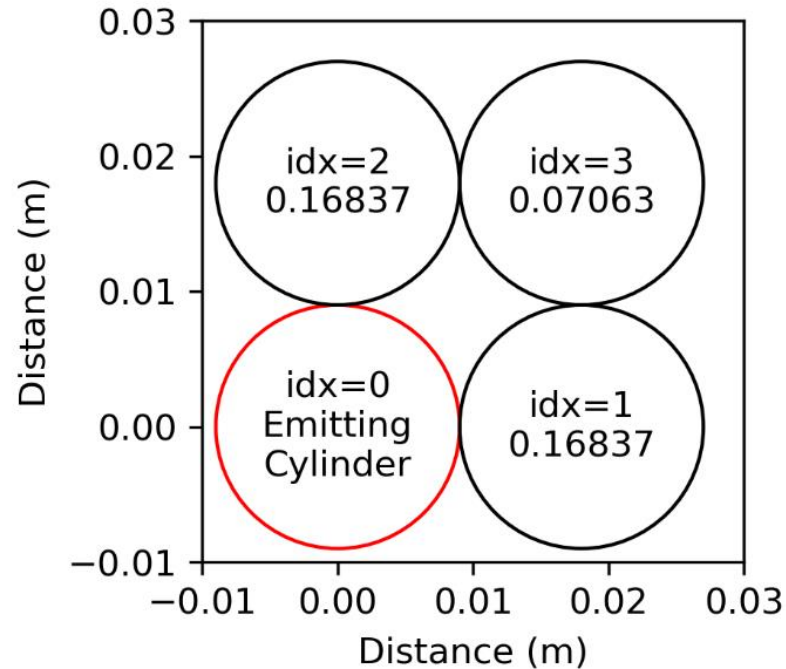
Blocking effect

Heat Transfer Analysis - Radiation

$$\dot{Q}_{rad} = \frac{\sigma(T_h^4 - T_c^4)}{\frac{1 - \varepsilon_h}{A_1 \varepsilon_h} + \frac{1}{A_1 F_{12}} + \frac{1 - \varepsilon_c}{A_2 \varepsilon_c}} = A_1 F_{12} \sigma(T_h^4 - T_c^4)$$



Validation

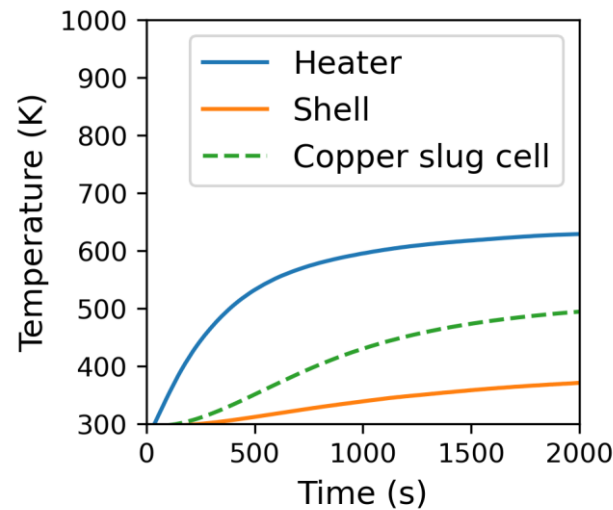
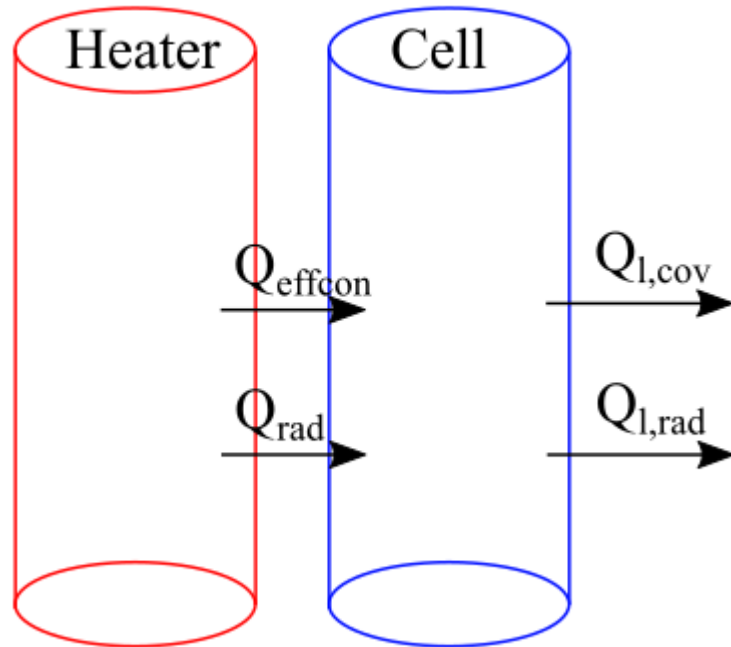


View factor example:
four cells

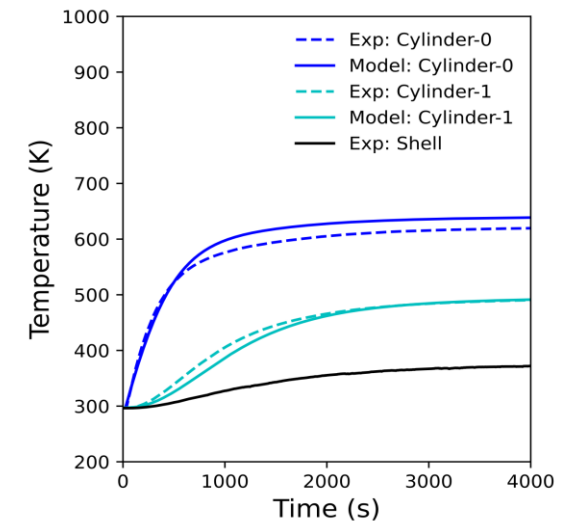
Heat Transfer Analysis - Effective Conduction

For target copper slug cell: $\dot{Q}_{rad} + \dot{Q}_{effcon} = m \frac{d(c_p T)}{dt} + \dot{Q}_{lossrad} + \dot{Q}_{lossconv}$

$$\dot{Q}_{effcon} = S(w)k_{air}(T_1 - T_2), \quad S(0) = 1.23$$



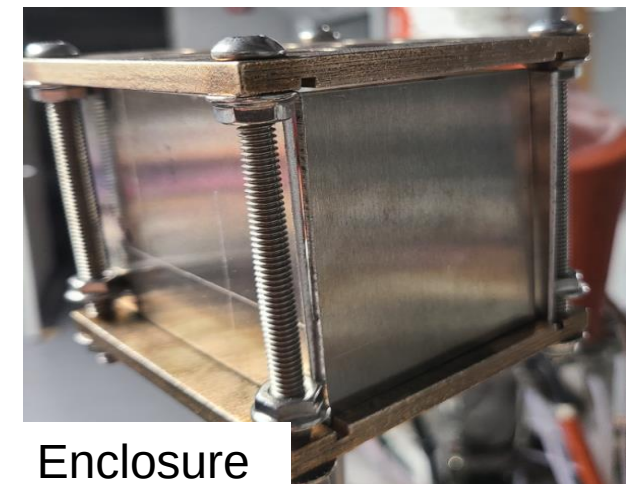
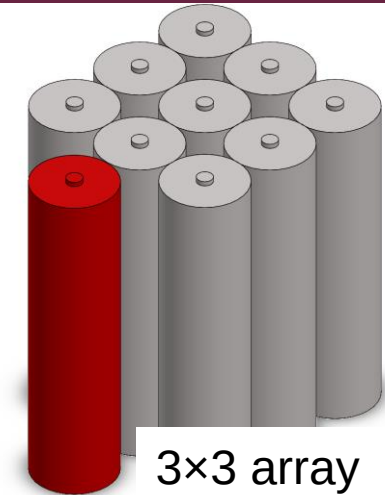
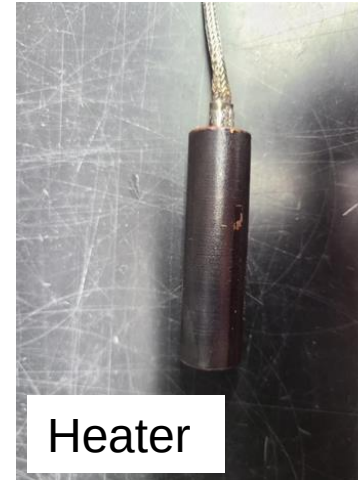
Temperature of heater and copper slug cell



Comparison of modeled and measured

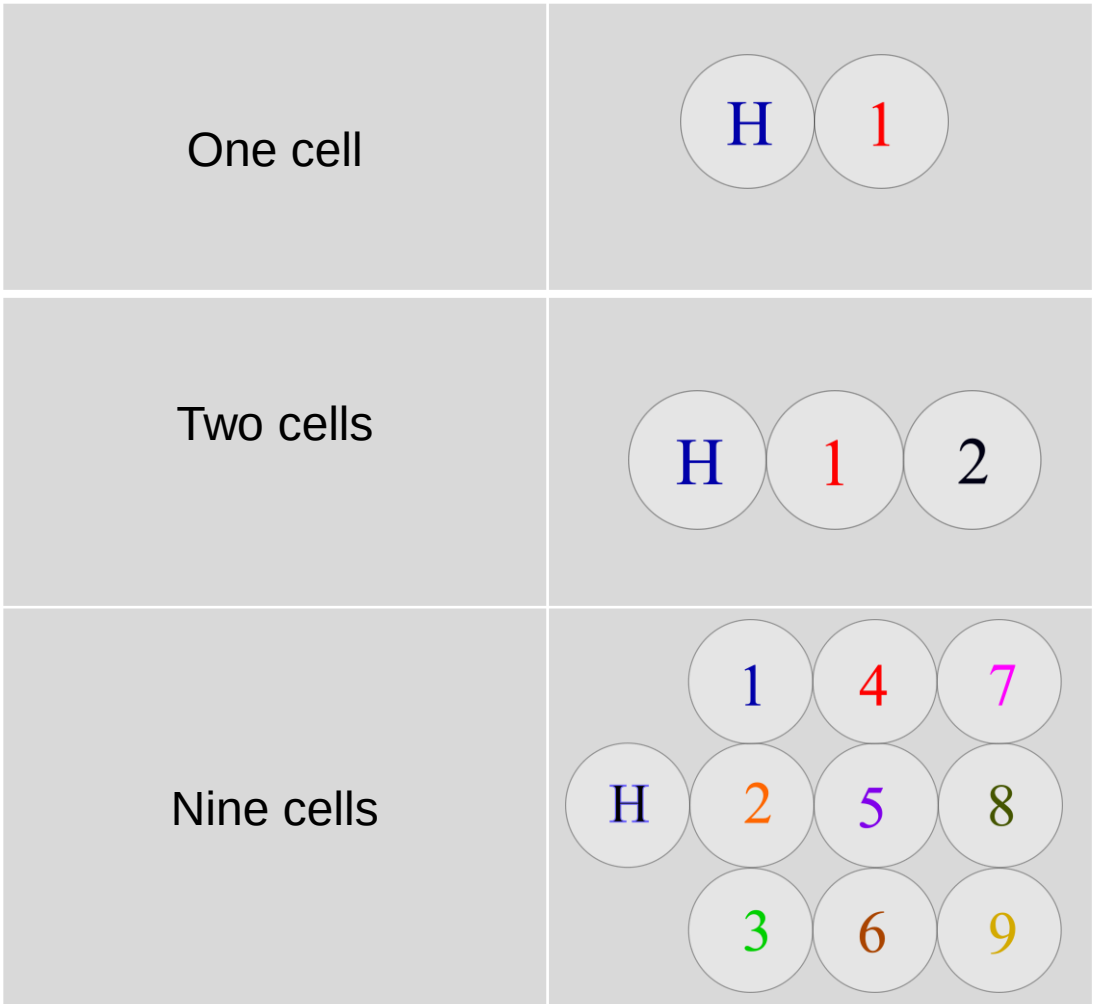
Thermal Runaway Propagation Test Design

- Heater: cartridge heater built inside 18650 form-factor copper slug (50 or 100 W)
- All surfaces coated black
- Two end-surfaces insulated
- Cell temperature measured by type-K TC welded to surface

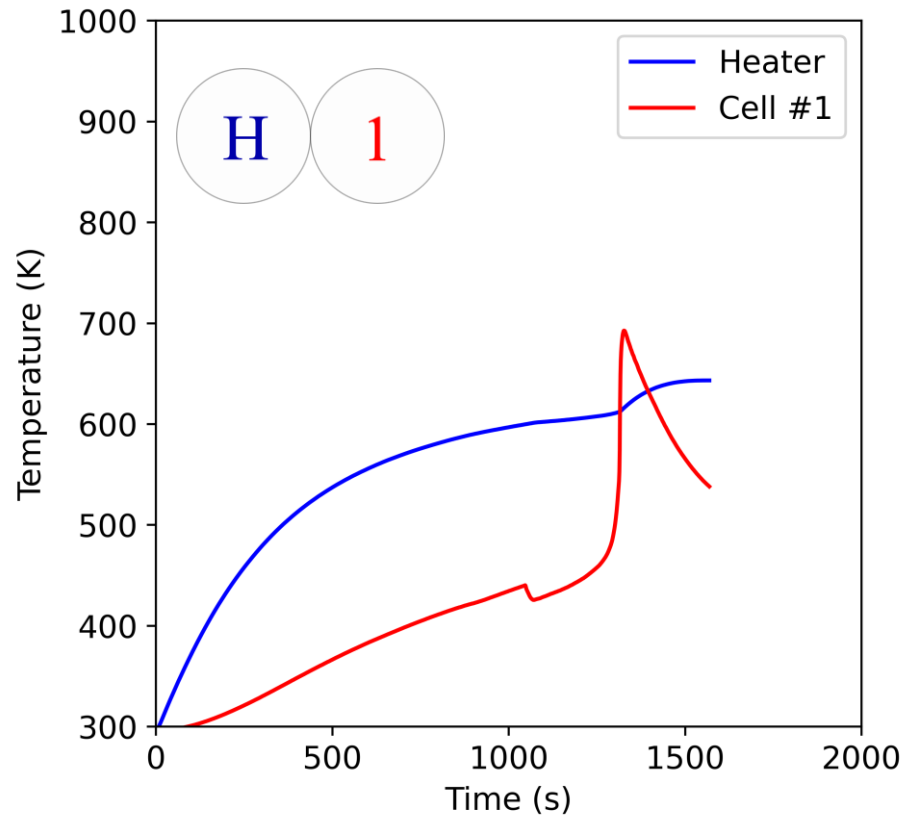


Thermal Runaway Propagation Test

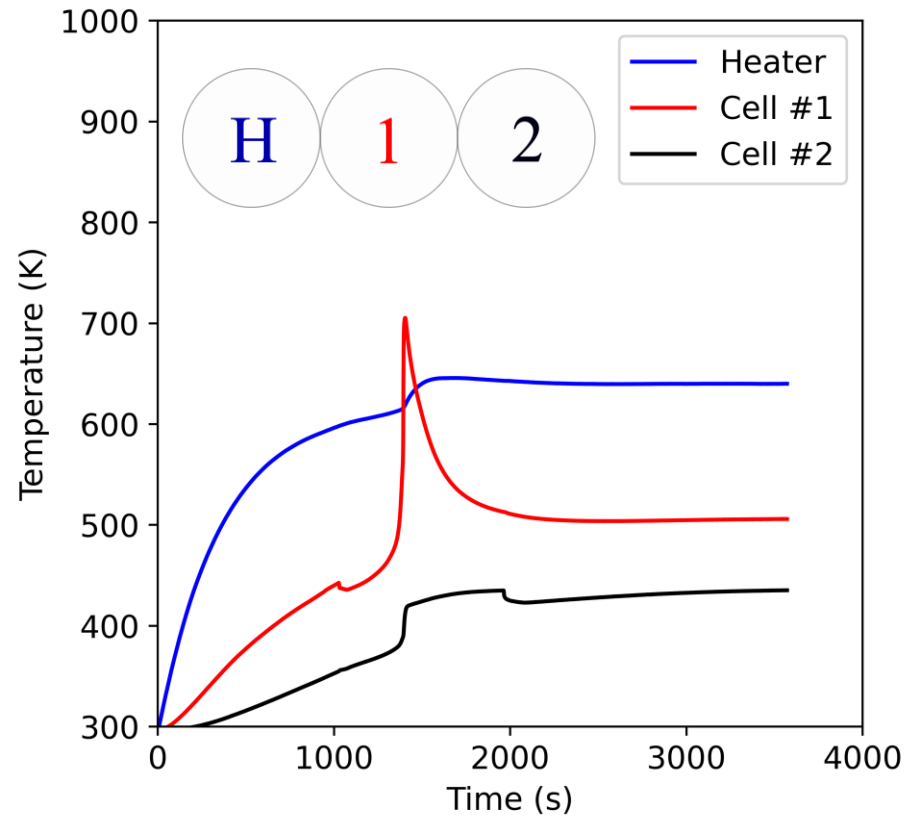
Model	Tenergy LCO	K2 Energy LFP
Cathode / anode	LiCoO ₂ / C	LiFePO ₄ / C
Mass without packaging (g)	43.6 ± 0.2	38.2 ± 0.1
Electric energy at 100% SOC (kJ)	39	17.3



Thermal Runaway Propagation - LFP



Mass loss: 14.4~15.4%



Mass loss: 13~20%

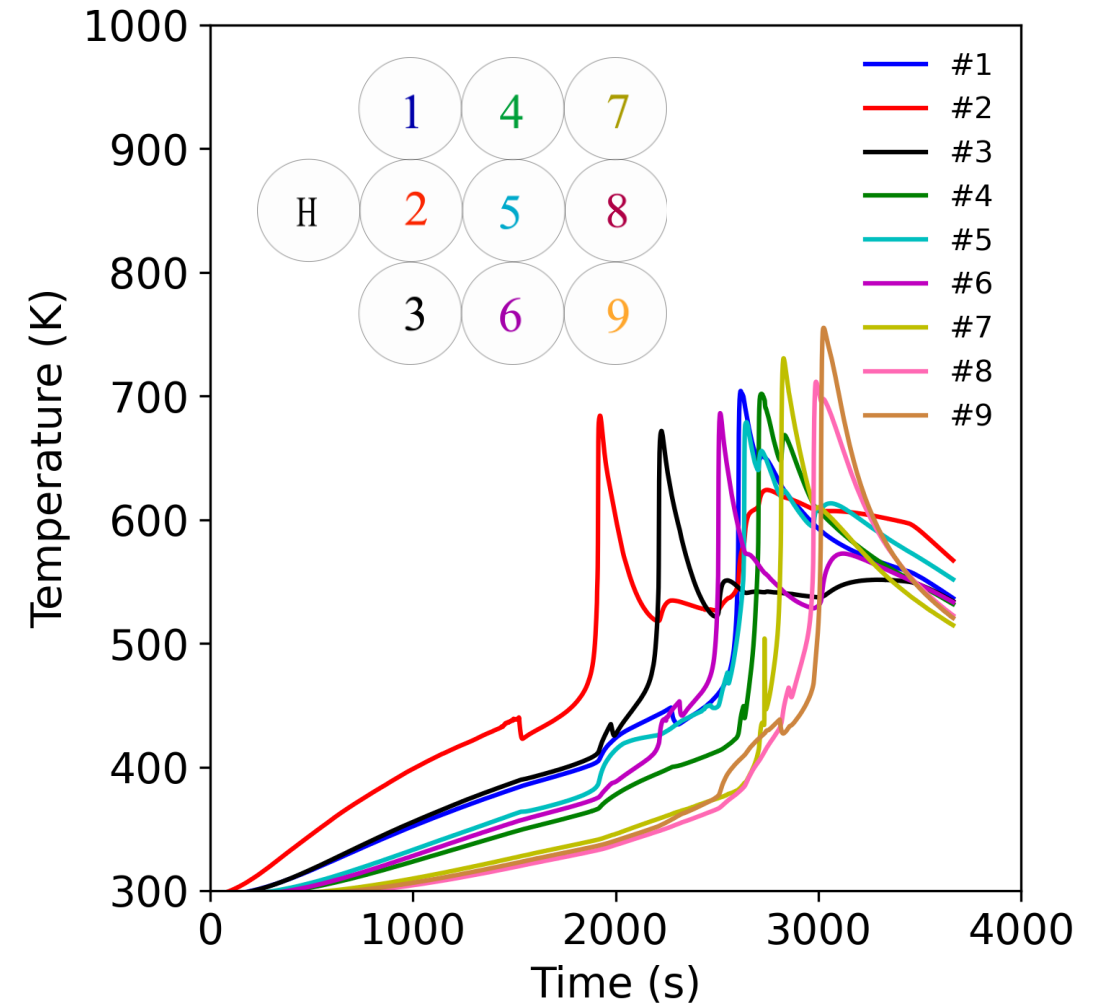


Thermal Runaway Propagation Test Result - LFP

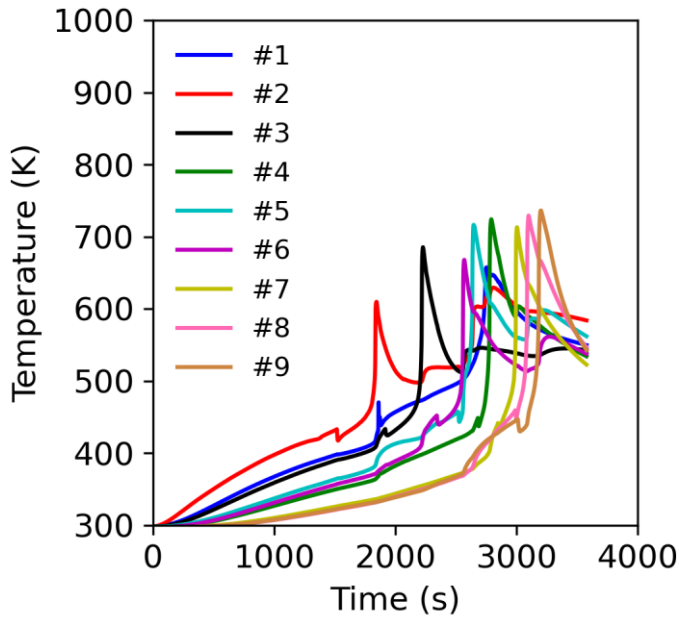
- Thermal runaway propagates to all cells
- Propagation accelerates



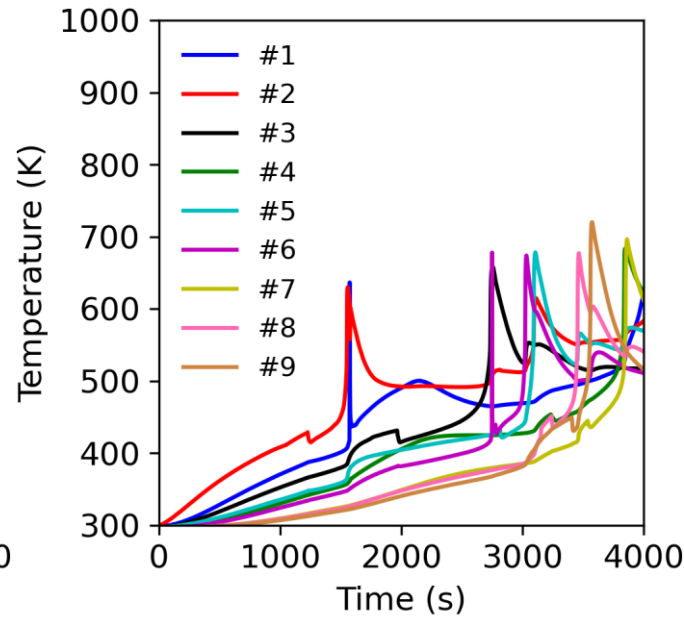
Test 3



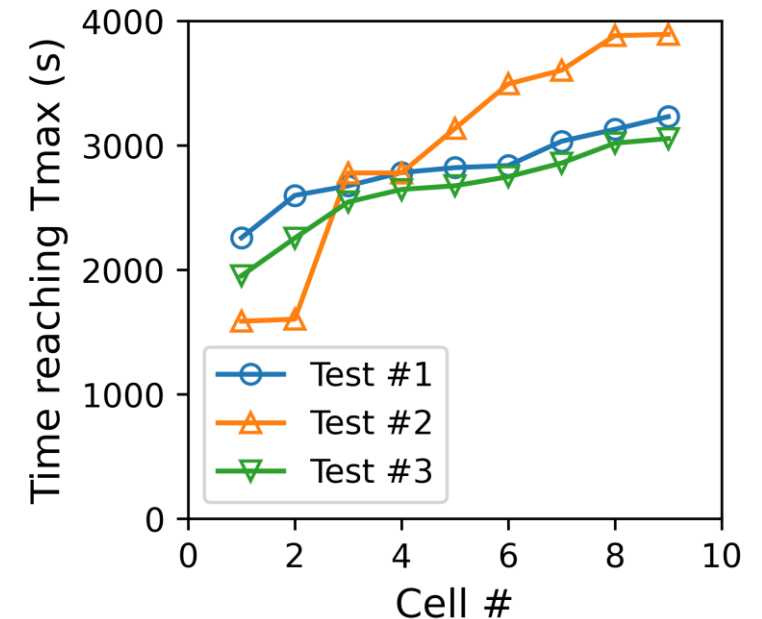
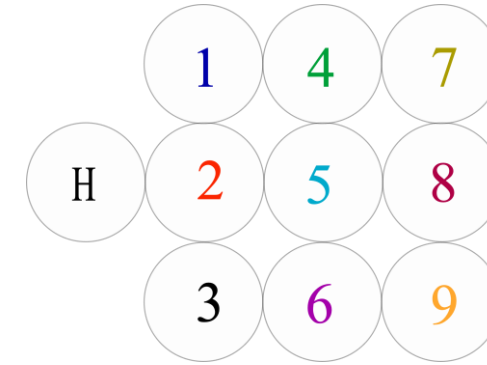
Thermal Runaway Propagation Test Result - LFP



Test 1



Test 2

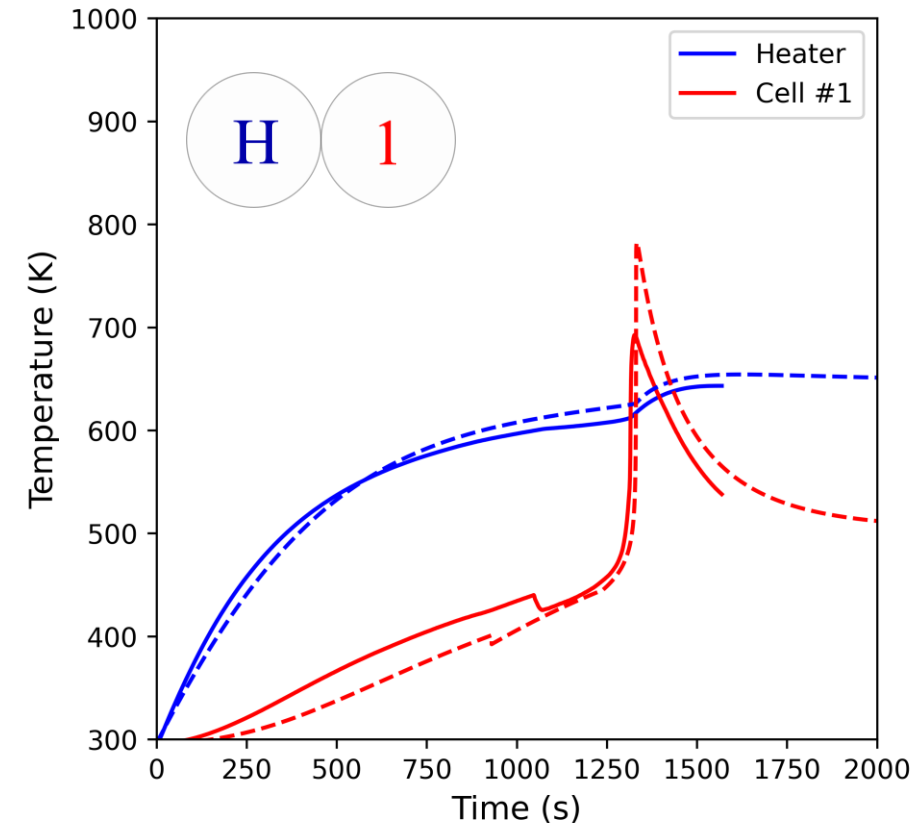


- Thermal runaway propagation path varies
- Stochastic feature

Network Modeling – 1 cell

- Neglect the heating effect of ejected materials
- Shell was not modeled, the measured temperature is used as model boundary condition

$$\frac{dU_i}{dt} = \dot{Q}_{i,IHG} - \dot{m}_{i,vent}h_{vent} - \dot{Q}_{i,l} + \sum_{j \neq i} (\dot{Q}_{j,i,rad} + \dot{Q}_{j,i,con})$$



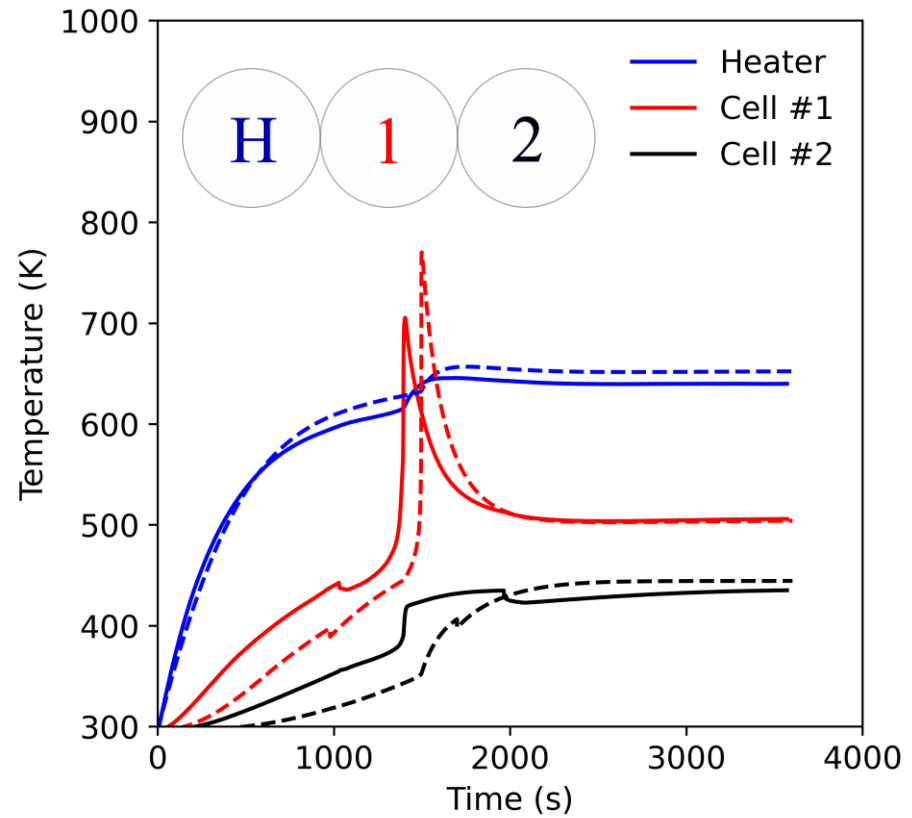
Dash line: model

Solid line: measured



Network Modeling –2 cells

- Model captures thermal runaway behavior

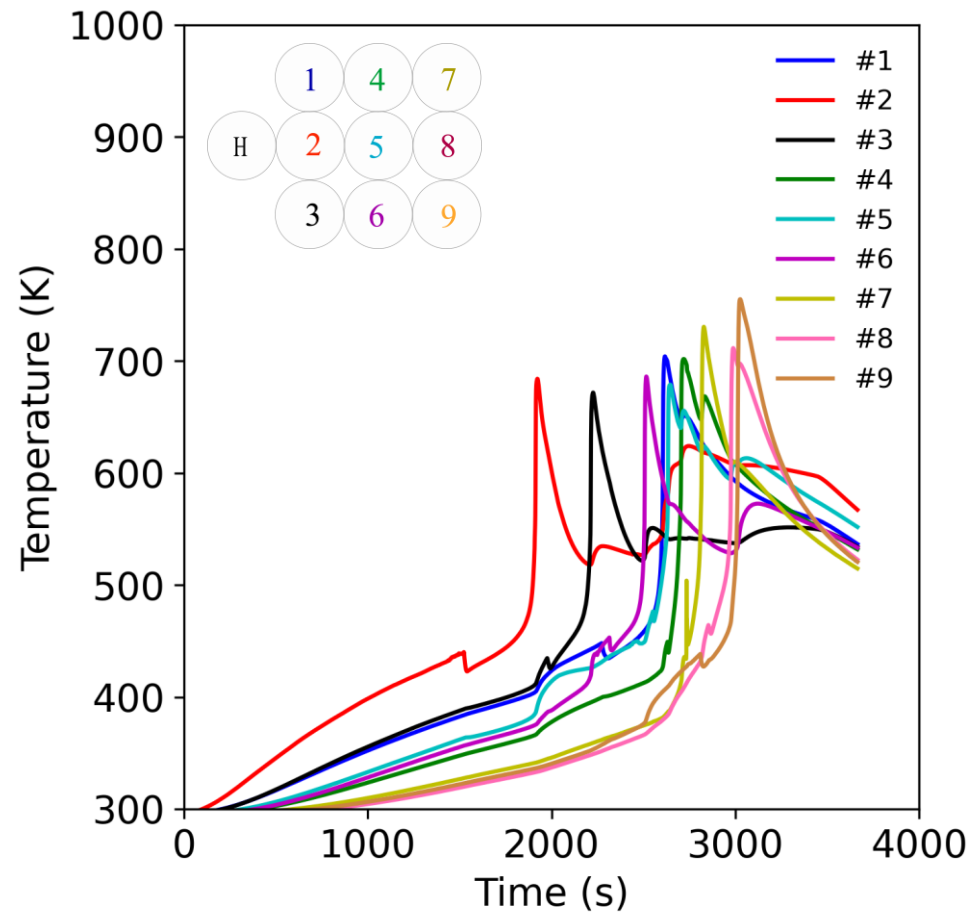


Dash line: model

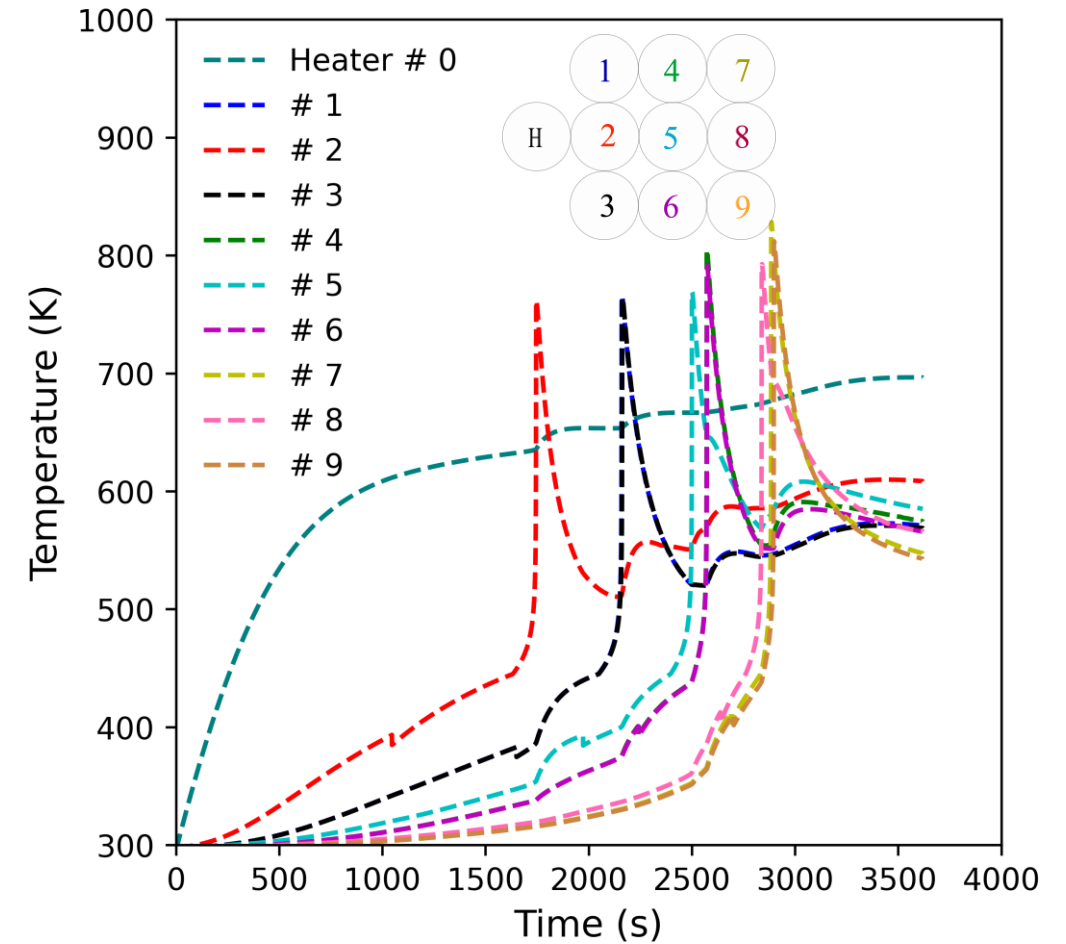
Solid line: measured



Network Modeling – LFP 9 Cells

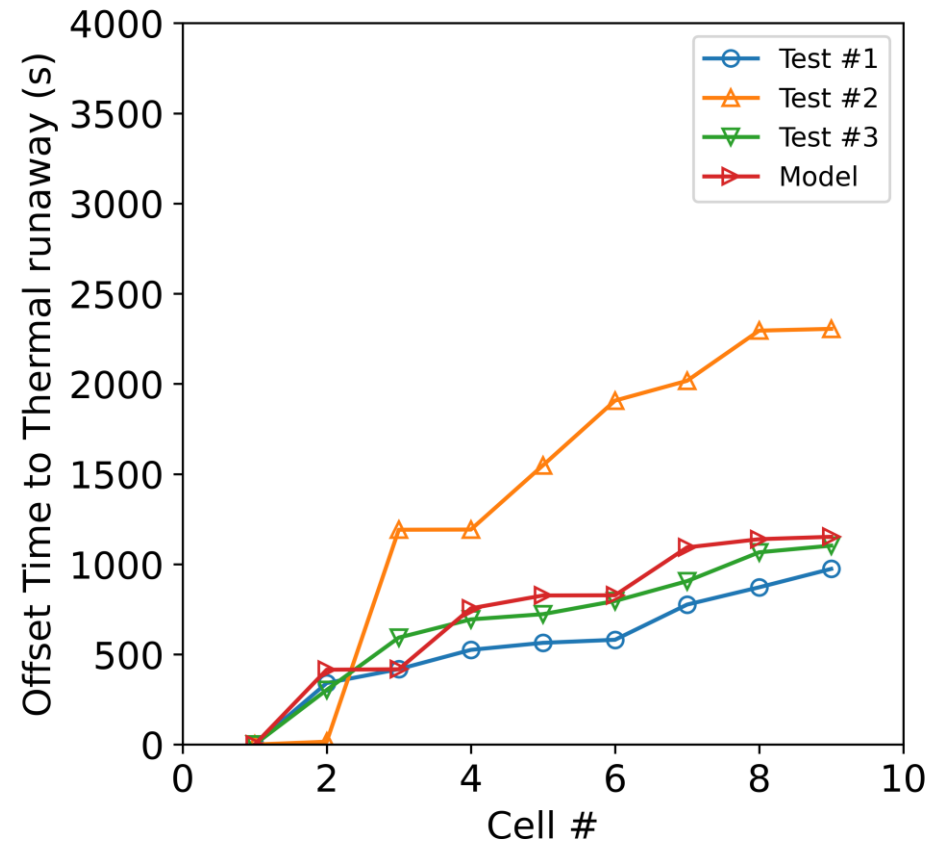


Experiment, test 3



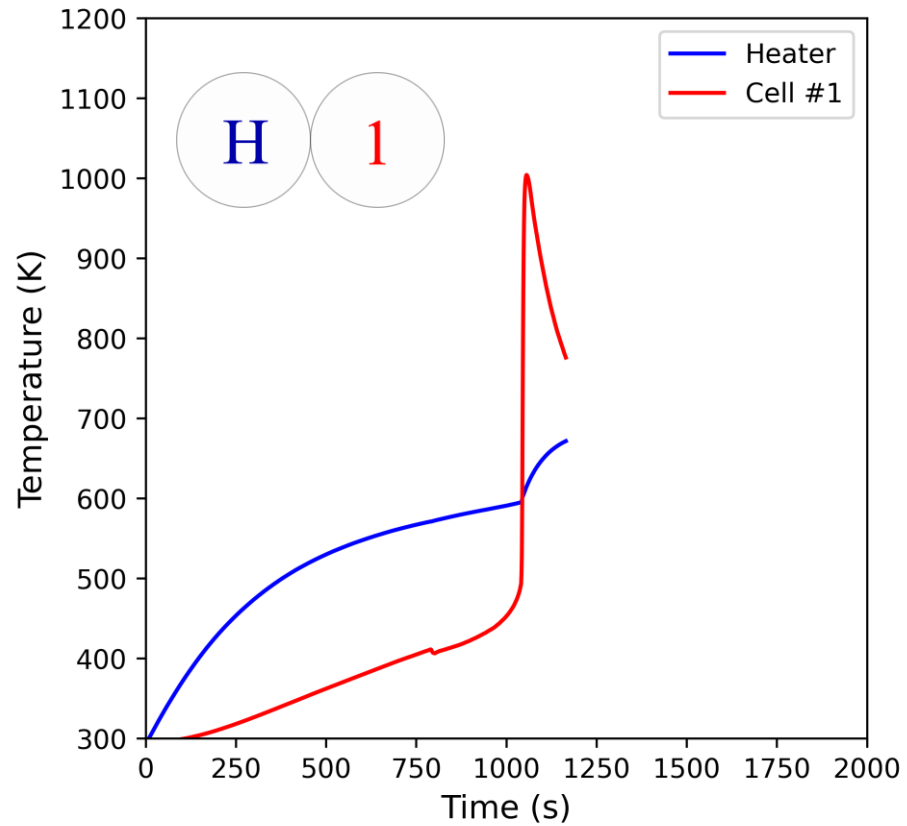
Model

Network Modeling – Takeaways

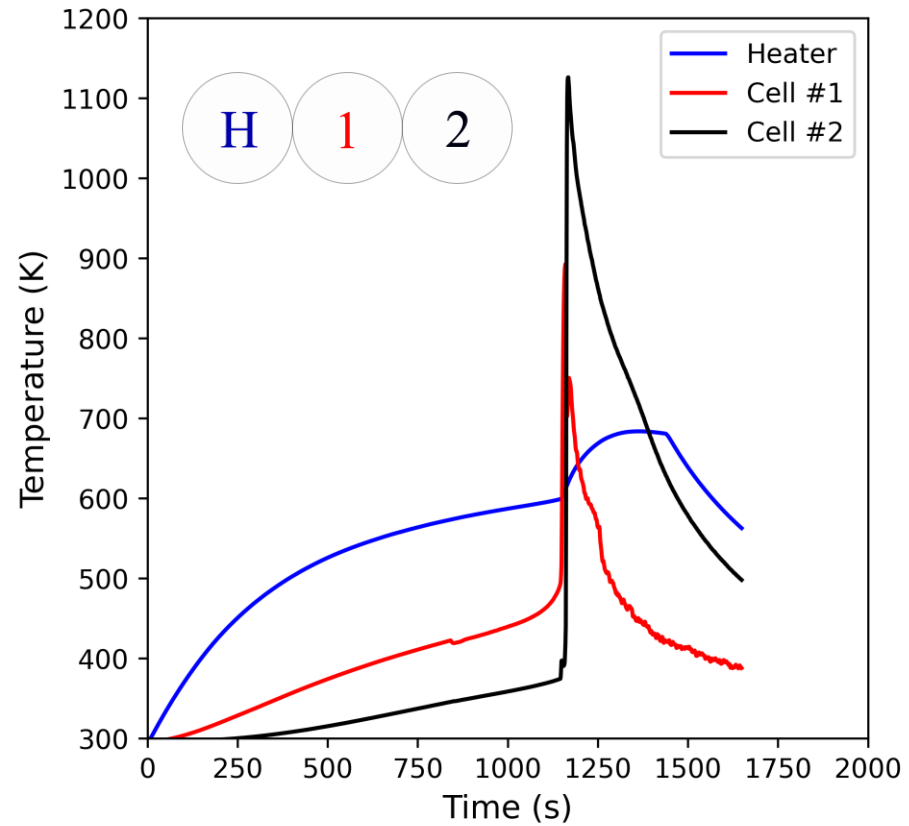


- Network model captures the TRP of LFP cells

Thermal Runaway Propagation Test Result - LCO



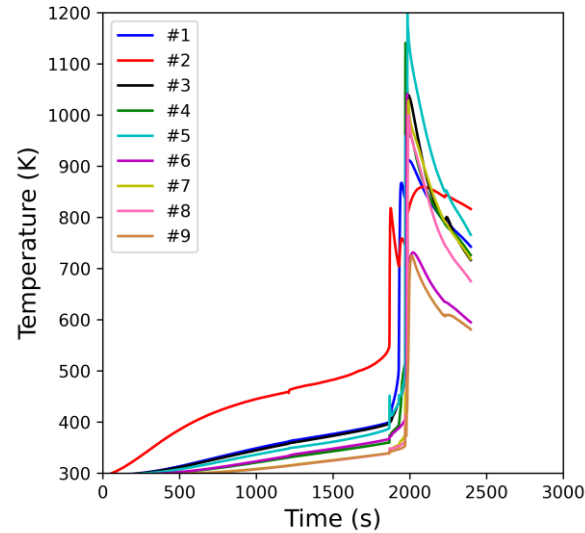
Mass loss: 52%



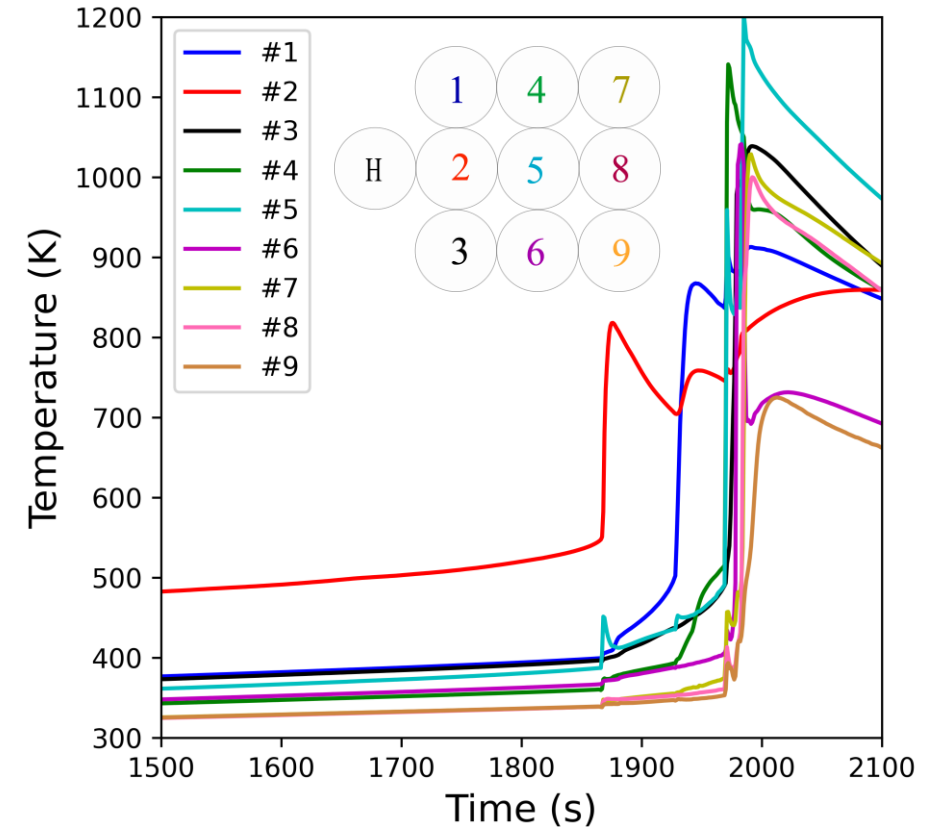
Mass loss: 40~74%

Thermal Runaway Propagation Test Result - LCO

- Propagation rate increases
- Some cells burst and greater mass loss compared to LFP

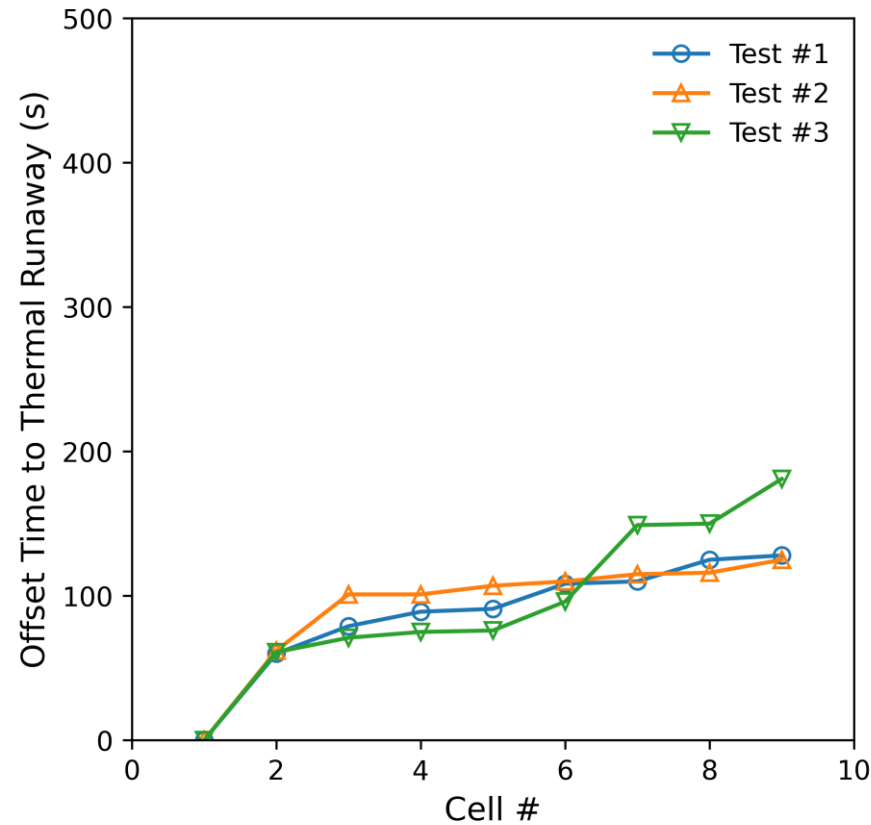


Test 2

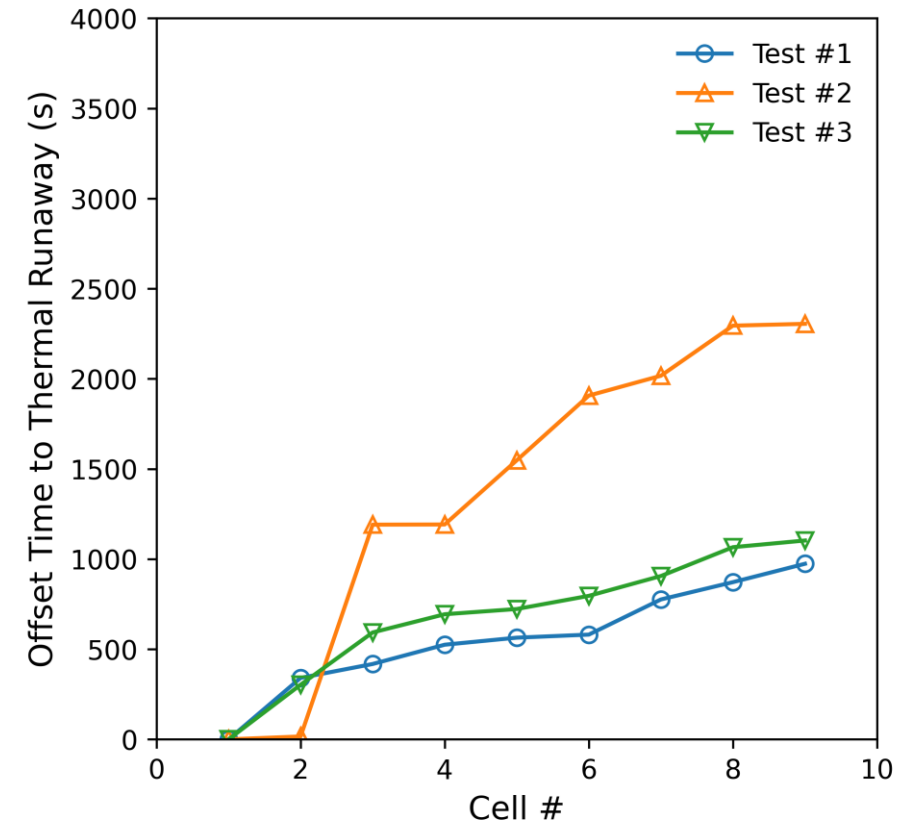


Thermal Runaway Propagation Test Result

- Time to thermal runaway offset by the first cell TR time
- TRP rate
 - LCO >> LFP

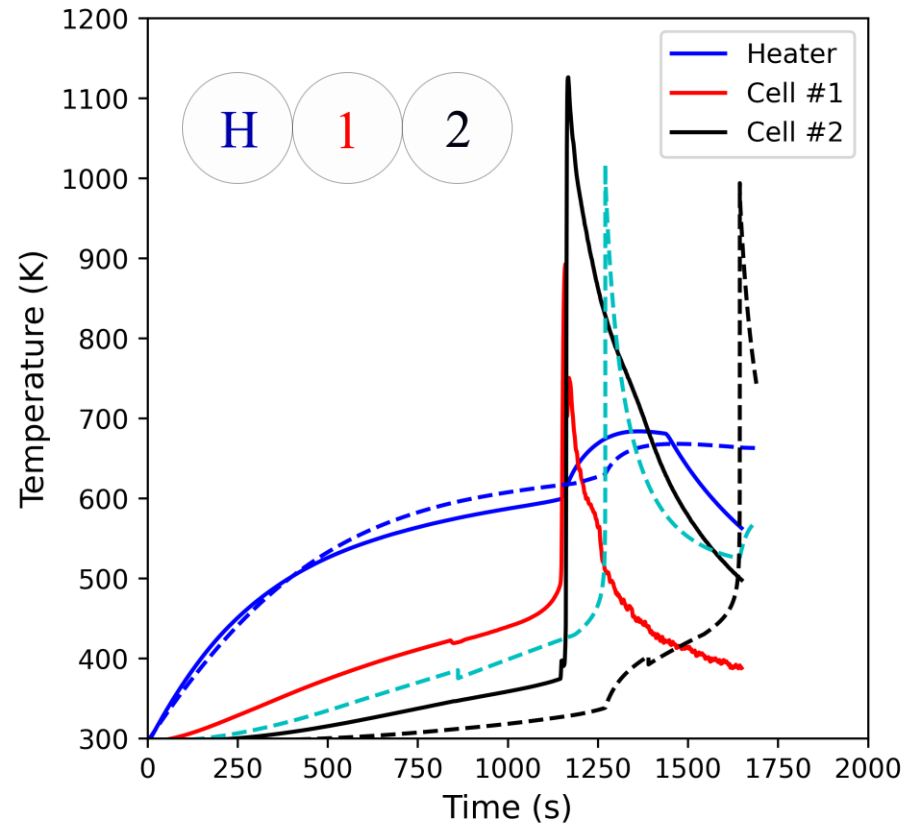
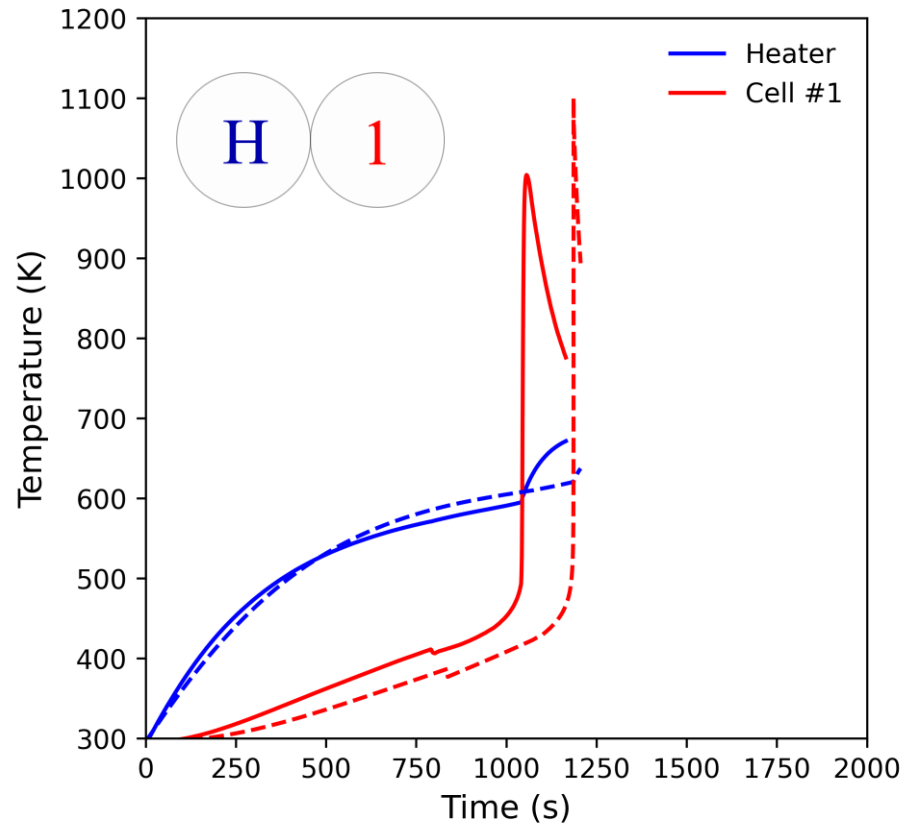


LCO



LFP

Thermal Runaway Propagation Modeling - LCO

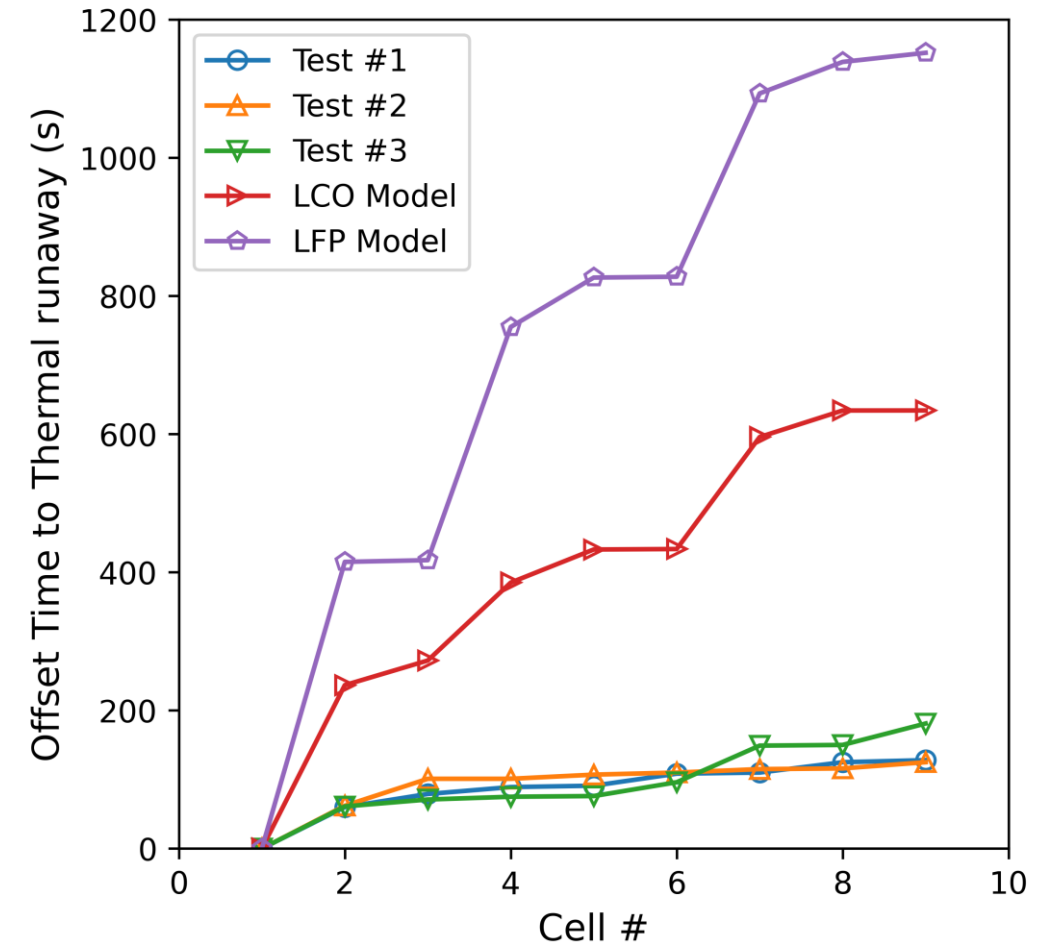


Dash line: model
Solid line: measured

Network Modeling – LCO 9 Cells

- Model underpredicts propagation rate
 - Energy from ejected materials

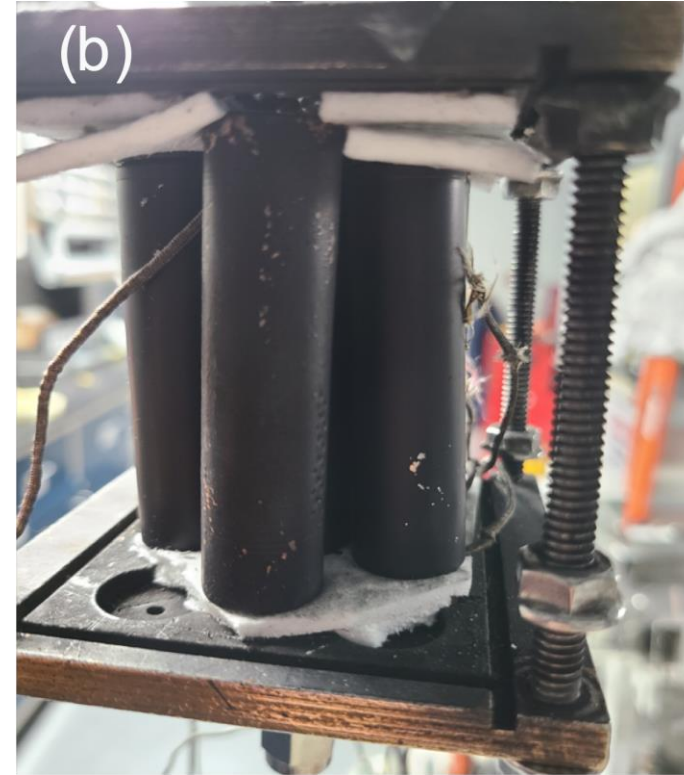
$$\frac{dU_i}{dt} = \underbrace{\dot{Q}_{i,IHG} - \dot{m}_{i,vent} h_{vent}}_{\text{Cell-level model}} + \sum \dot{Q}_{i,s} + \underbrace{\sum_{j \neq i} F_{ji} [\dot{m}_{j,ej,solid} h_{ej} + \dot{m}_{j,ej,gas} (h_{ej} - h_{T_i})]}_{\text{Energy transfer from ejecta of cell \#j to \#i}}$$



Experimental Evaluation of Ejecta Heating in TRP

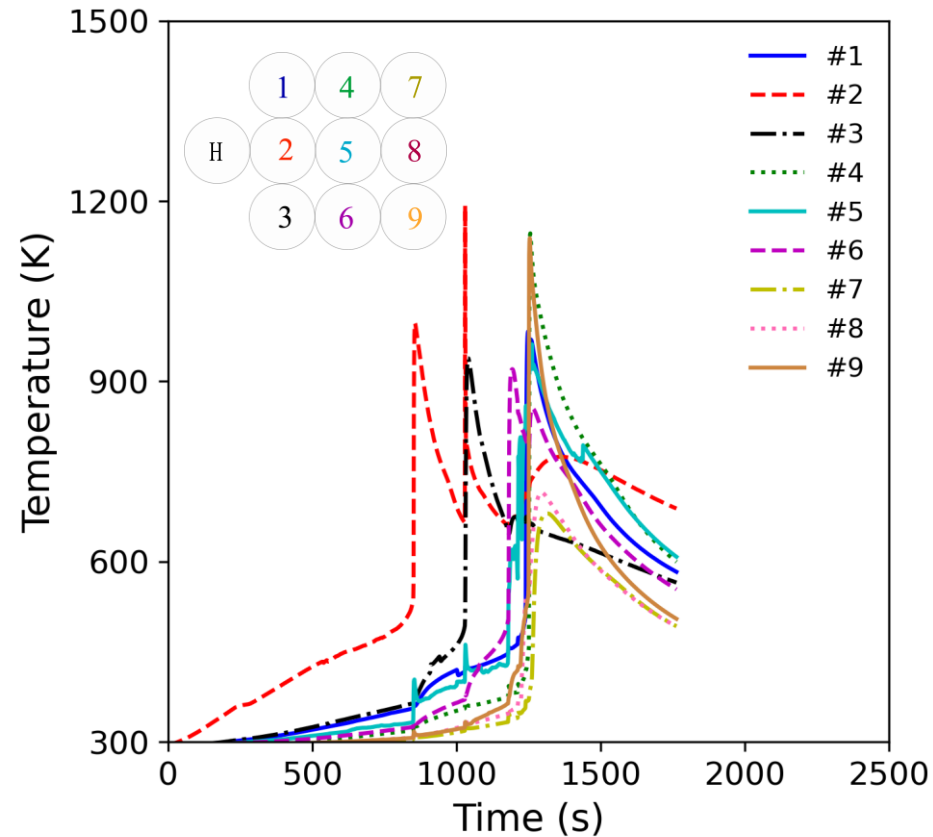


Open space

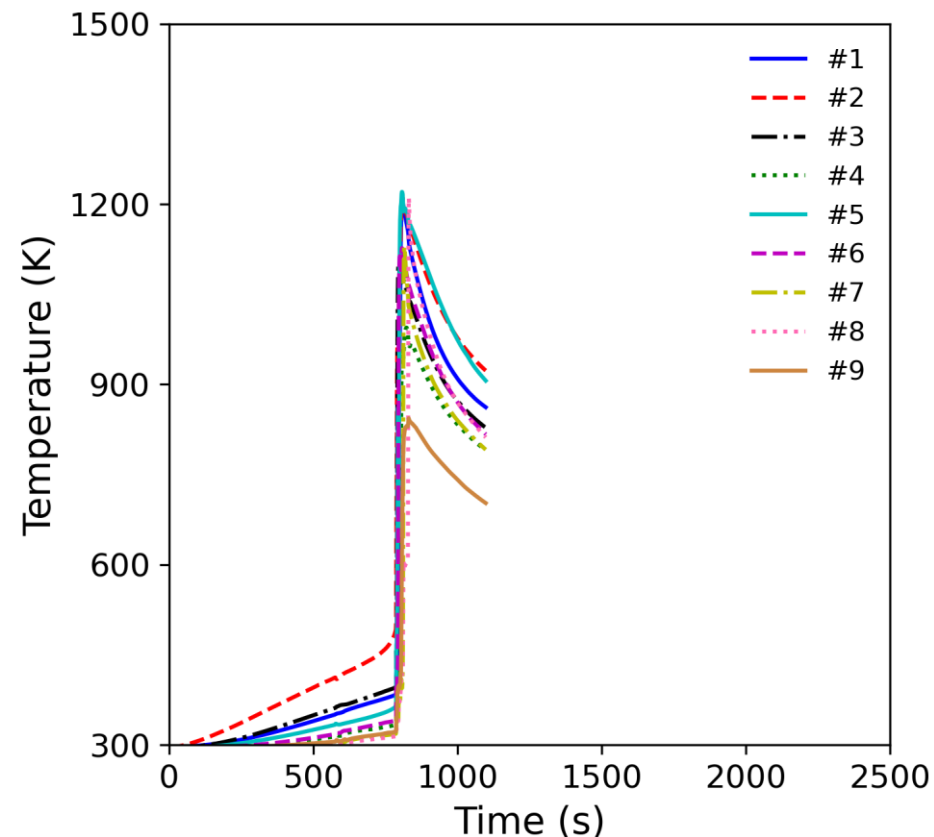


Enclosure

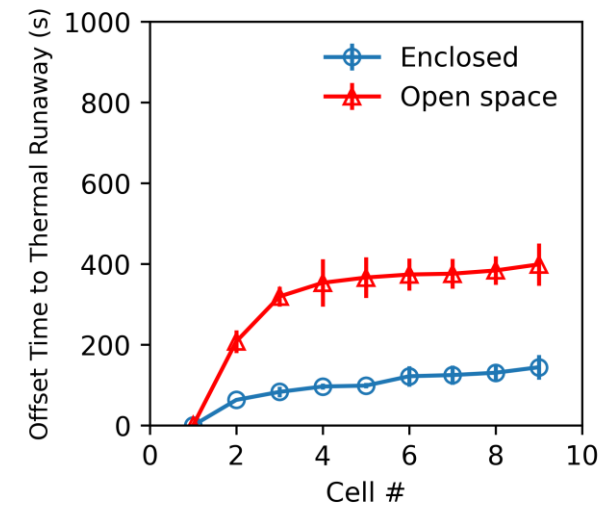
Experimental Evaluation of Ejecta Heating in TRP



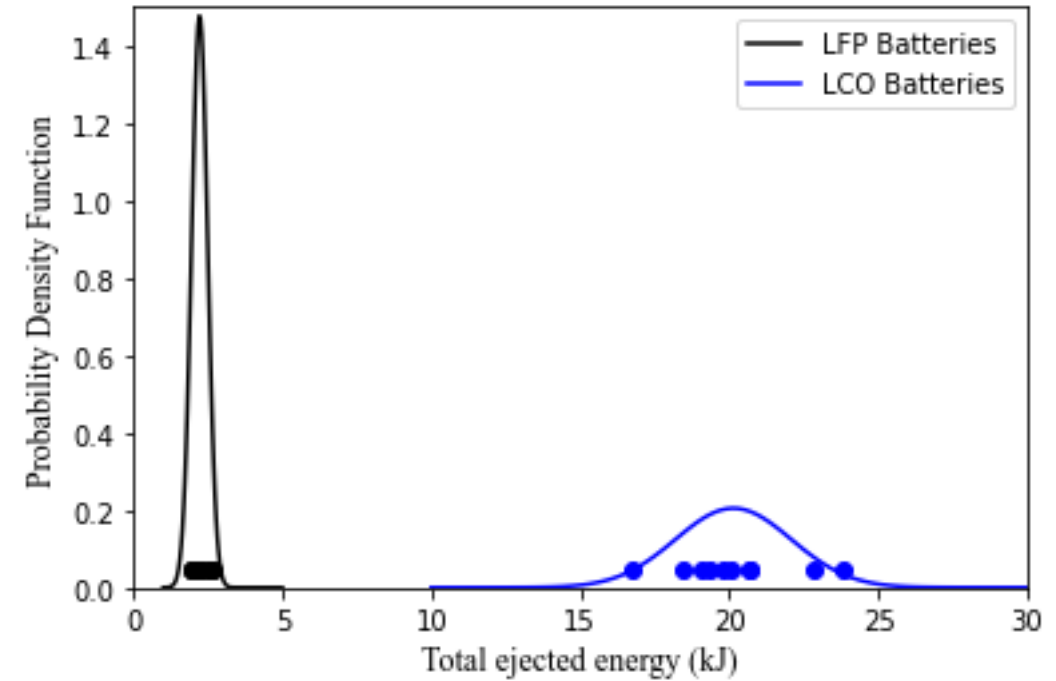
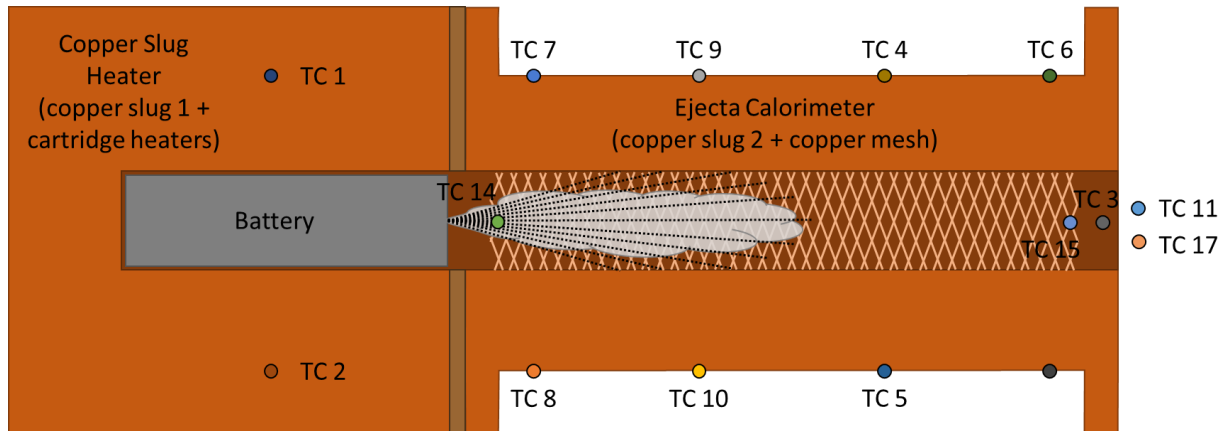
Open space,
100 W heater



Enclosure,
100 W heater



Measurement of Ejecta Energy



Probability Density Function of Ejecta Energy

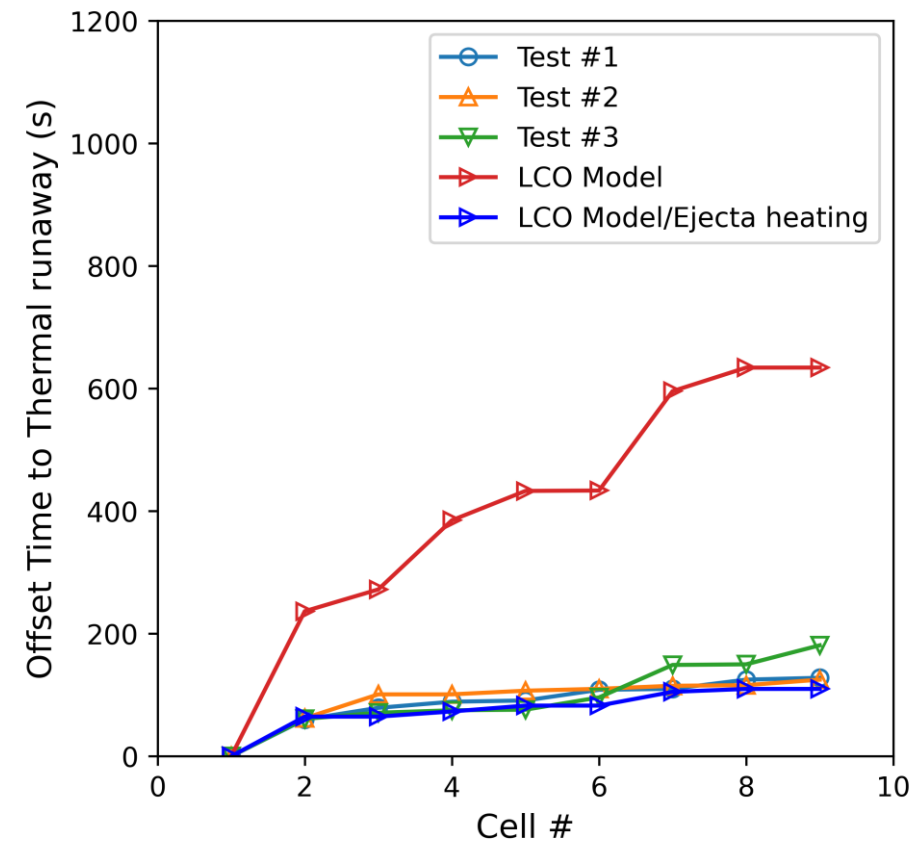
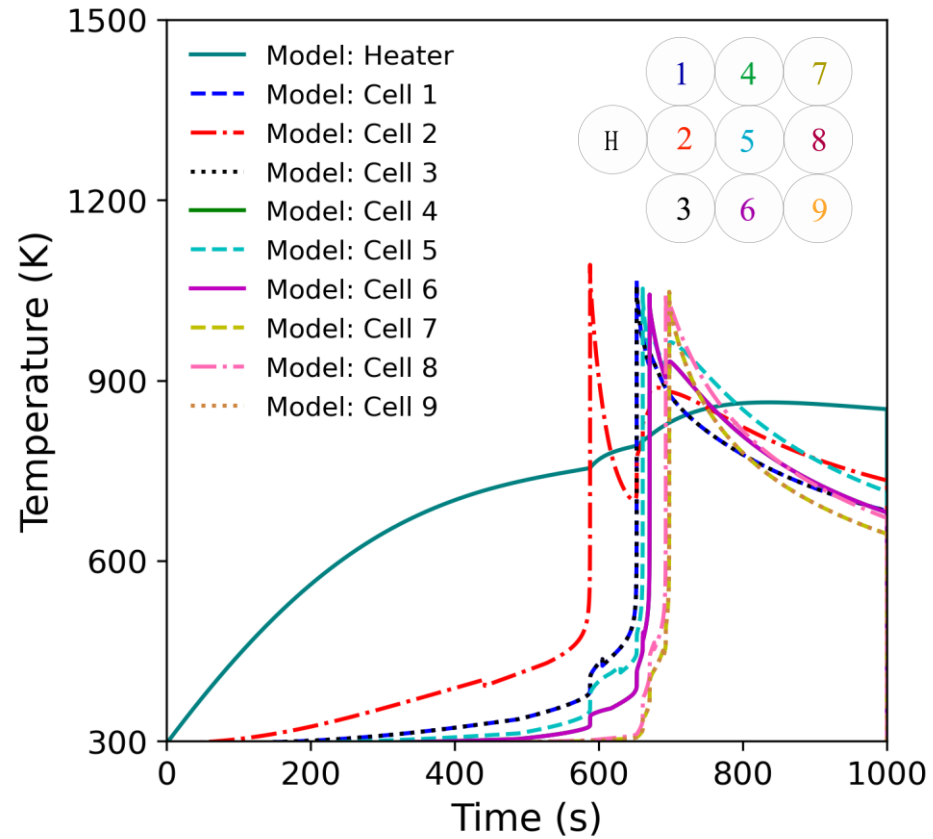
For LCO cell: $Q_{ej} = 20.14 \pm 2.1 \text{ kJ}$

$$m_{ej} = 20 \text{ g}$$

Assuming: $C_{ej} = 1100 \text{ J/gK}$

$$T_{ej} = 1232 \text{ K}$$

LCO TRP Modeling with Ejecta Heating



Summary

Network
model for
engineering
calculation

Successful
prediction of
TRP of
simple
module

Research
approach can
be applied to
other
chemistry



Future work

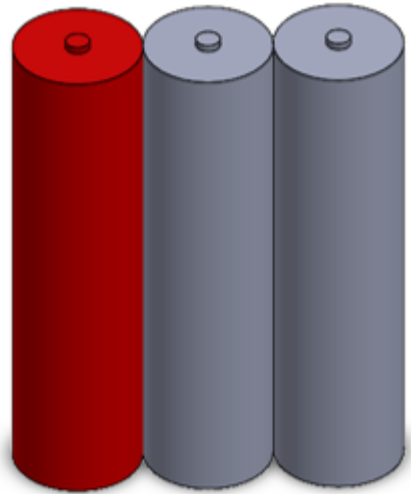
Real
module
test

Conjugate
heat
transfer

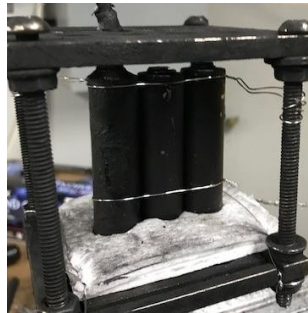
Coupling
with CFD



Effect of Geometry on Ejecta Heating on TRP



Open



Half-Open



Enclosed

