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A MODELING PERSPECTIVE ON THERMAL RUNAWAY PROPAGATION THROUGH THE MODULE AND RACK SCALES

Safety & Reliability

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Sandia National Laboratories

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U.S. DEPARTMENT of ENERGY

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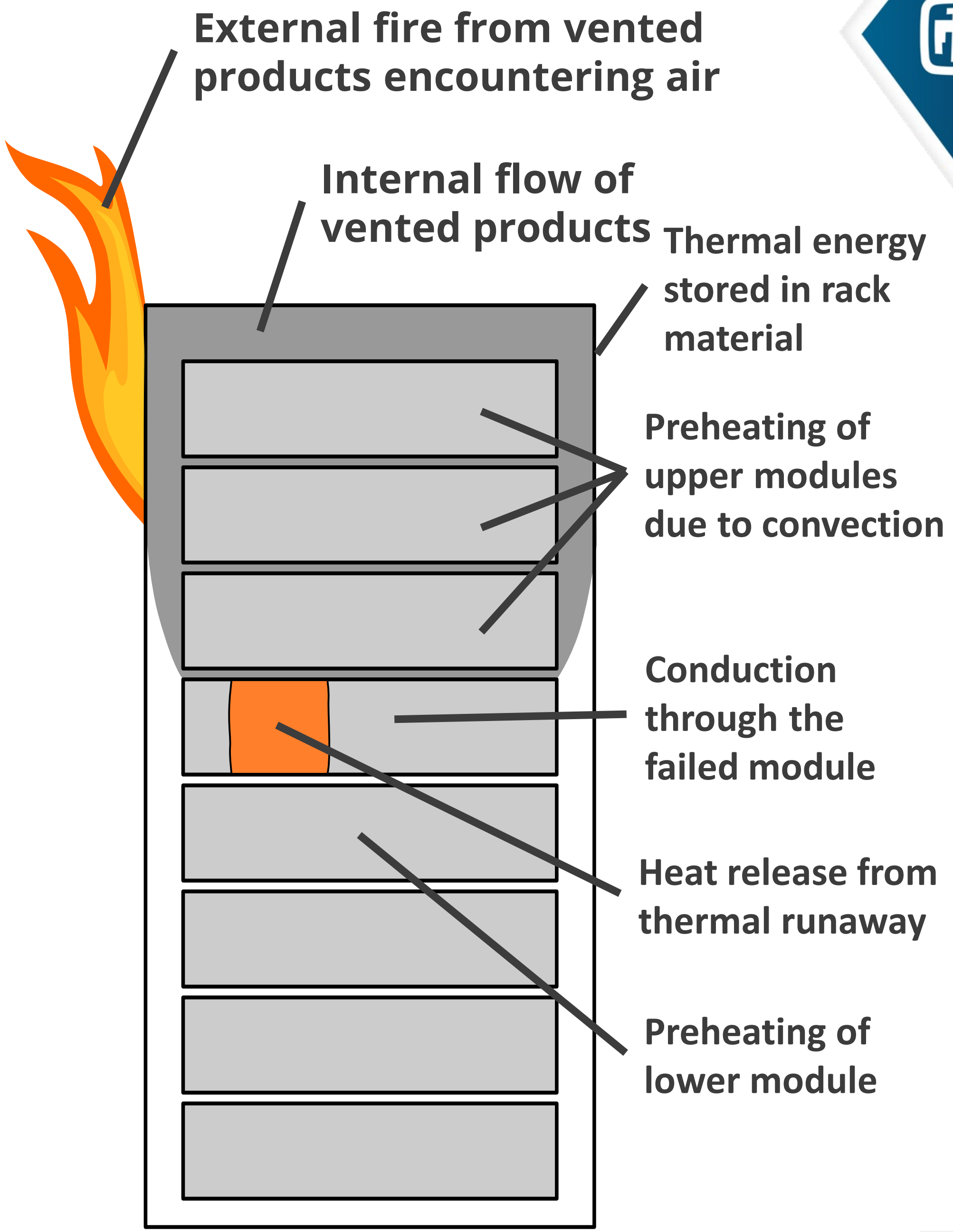
PROBLEM

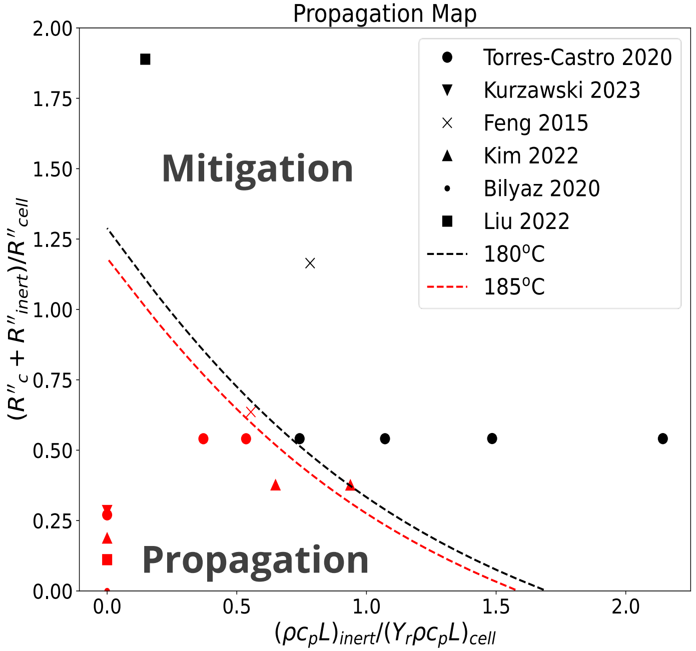
- Thermal runaway may occur in a single cell of an energy storage system, and the heat generated during this process may be sufficient to cause thermal runaway in nearby cells
- These events can be catastrophic, leading to hazards for the public and first responders, and damaging expensive equipment
- Scale of the problem can be related by the heat transfer:
  - Fast: internal cell heating (10 – 100 sec)
  - Medium: cell-to-cell heat transfer (5 – 30 min)
  - <u>Slow: module-to-module interactions</u> (15 – 90 min)
- How can we predict module-to-module propagation with little available computational or experimental data?



PROJECT OVERVIEW

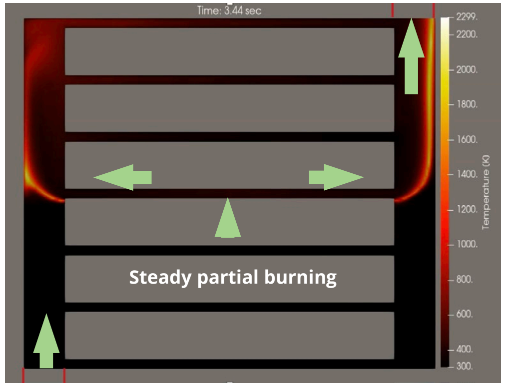
- **Goal**: Improve prediction capabilities of module-to-module thermal runaway propagation and the flaming/non-flaming behavior of flammable vent gases at the rack scale
- **Objective: *developing system design guidelines*** that can be used to reduce the likelihood of cascading thermal runaway at the module-to-module scale.
- **Current Practice** relies on incident forensic analysis and testing that can only cover a small range of parameter space to develop ‘safe’ systems. Reliance on a few testing methods (i.e. UL9540A) means systems are well designs against one type of incident but not tested against others.
  - First responder inclination to “let it burn” does not help DOE objective to ***Stabilize Grid Services*** unless designs inherently minimize propagation.
- **Why SNL:** Past SNL work has developed ***propagation/mitigation guidelines*** for cell-to-cell propagation within a module. This work extends this philosophy to rack-scale system design. The goal remains to ***stop cascading propagation at the earliest point possible***, but ***develop multi-layered protections***.
  - Modeling draws on SNL expertise in multi-physics simulation capabilities
  - Builds on joint experimental-modeling efforts to improve validation and data collection over a broad range of scenarios.

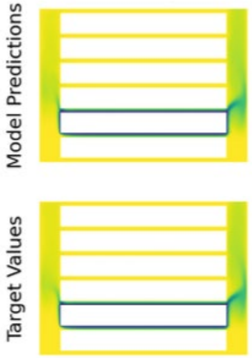
EPRI BESS Failure Database
https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database

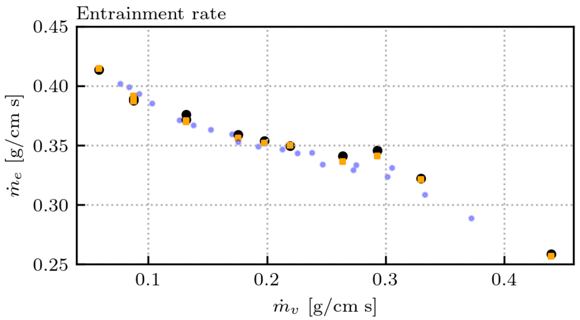


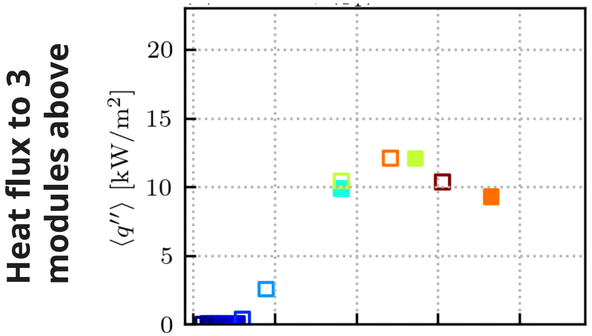
PROJECT OVERVIEW

- **Innovation**: SNL integrates three major thrusts
    1. Large-scale multi-physics predictive capabilities
    2. Reduced-order-model development
    3. Identification of key correlations (e.g. propagation/mitigation boundaries, buoyant air entrainment into flammable gas plumes)
- Duration: FY25 – FY26
- **Impact**: Improved understanding and new capabilities can be used to
    1. Assess likely safety aspects of the system-level design
    2. Be integrated as a tool into the BMS to sense and mitigate propagation (e.g., via energy redistribution as per SNL Safety & Reliability program 2022 results)
    3. Reduce large-scale ESS fires occurrence, increase ESS availability and reduce ESS insurance costs.
- Vertical/Investment Area: Safety & Reliability
- Supports strategic pathway to ***Stabilize Grid Services***: develop and promote advanced predictive safety protocols for energy storage systems, leverage AI to create digital twins and anticipate/predict safety incidents







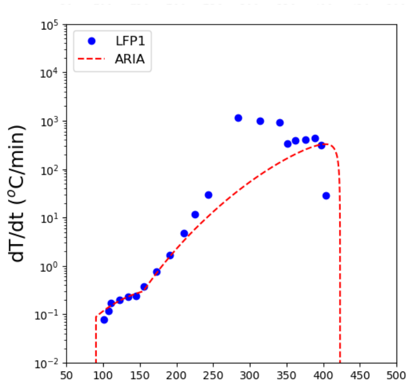


APPROACH

At each scale, we identify the core underlying physics and propose reduced mechanisms that support integration into larger scales

- Cell-scale:
  - Develop reduced chemical reactions to estimate heat source
- Module-scale:
  - Develop heat transfer model to predict cell-to-cell propagation
- **Rack-scale:**
  - **Develop fast-running, physics-based models to predict heat transfer between modules**

<u>Problem:</u> Convectively dominate flows are notoriously difficult to develop robust reduced-order models due to the nonlinear transport.



Shurtz, et al., *J. Electrochem. Soc.*, 165, A3878 (2018).
Shurtz, et al., *J. Electrochem. Soc.*, 165, A3891 (2018).
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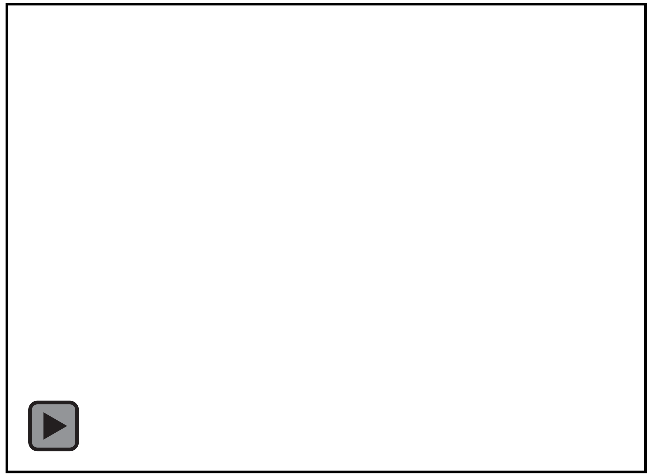
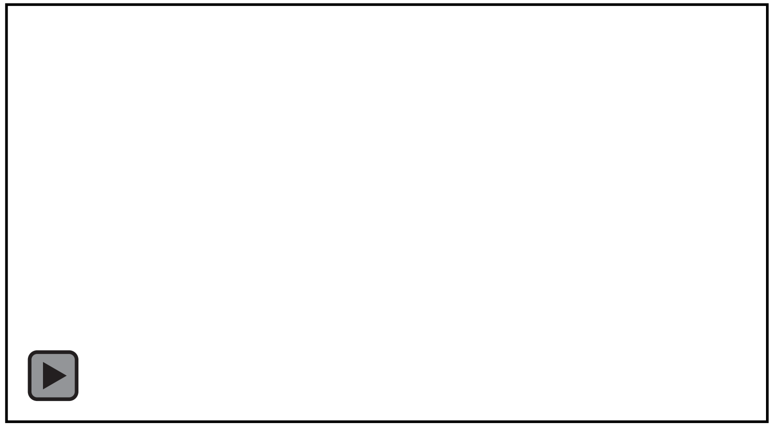
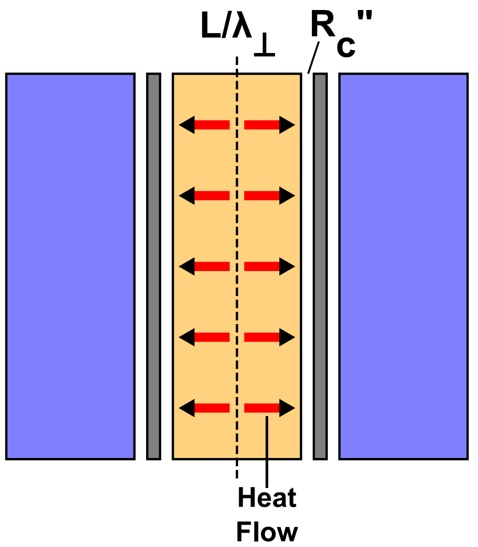
Kurzawski, et al., *Proc. Combust. Instit.*, 34 (2020)
Kurzawski and Shurtz., LIM1TR, *No. SAND2021-12281*. (2021)
Kurzawski, et al., *Fire Safety J.*, 140 (2023)
Kurzawski, et al., *in preparation* (2026)
***research in progress**

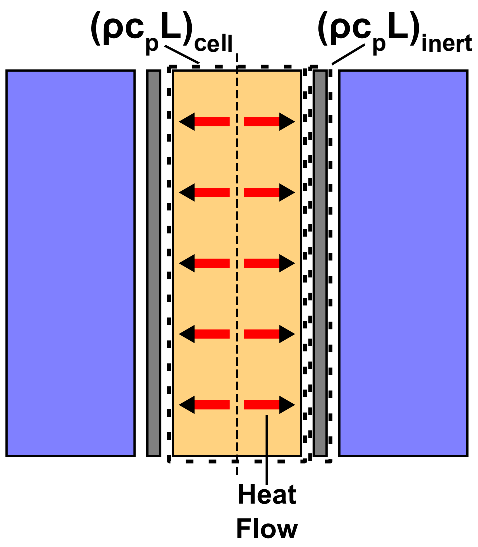


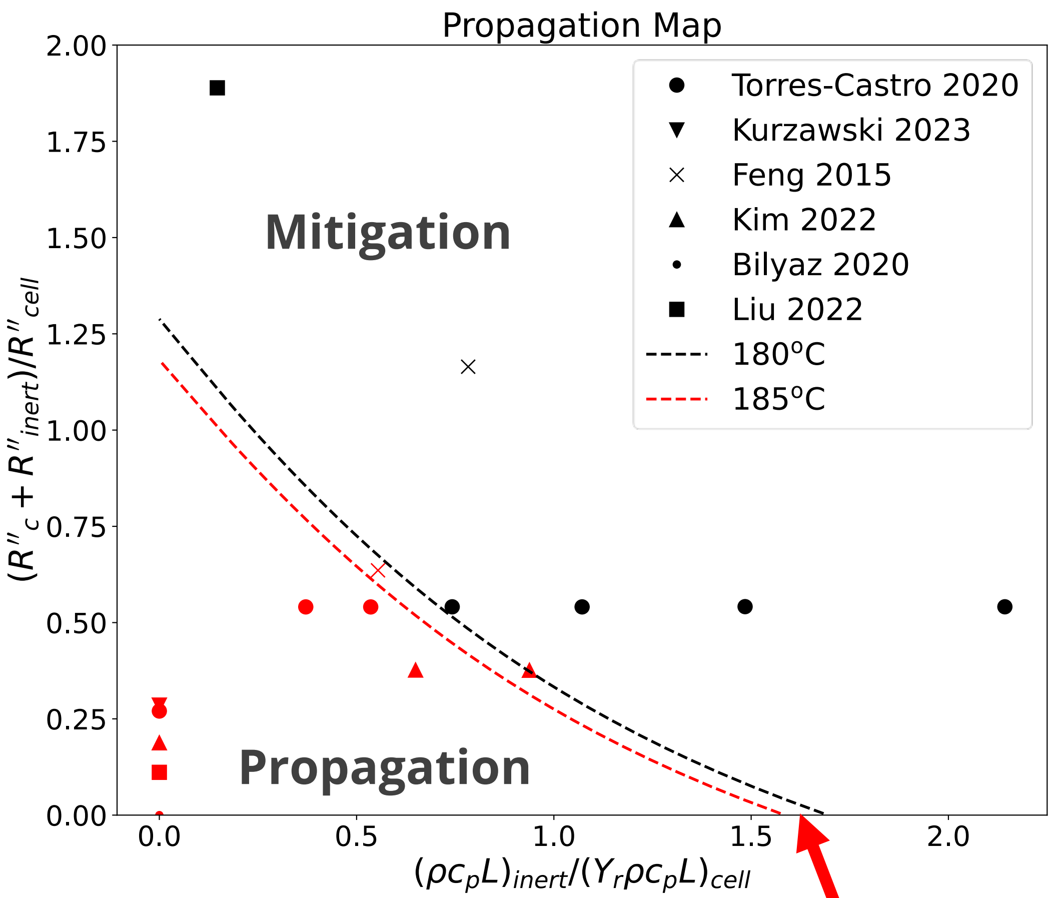


Qatramez et al., ASME J. Heat and Mass Transfer (2025).
Meehan, et al., Fire Safety J. (2026)
Meehan, et al., *J. Energy Storage* (2026)
***research in progress**

CELL-TO-CELL PROPAGATION/MITIGATION







Modeled T_{onset} boundaries

Key features

- Assume losses to ambient
- Range of cell sizes with different inter-cell materials
- Vertical axis: ratio of inter-cell resistance to internal resistance
- Horizontal axis: ratio of intercell heat capacity to heat capacity remaining in cell after venting

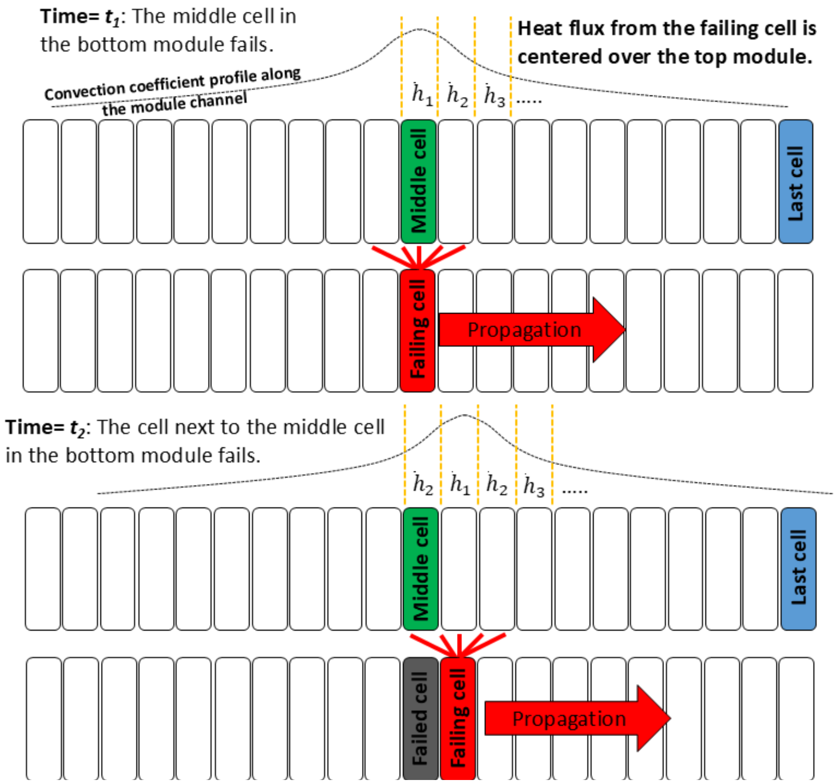
Main uncertainties

- Mass loss
- Contact resistance

Impact: size, material, etc. of inert material is a design choice.

VENTING

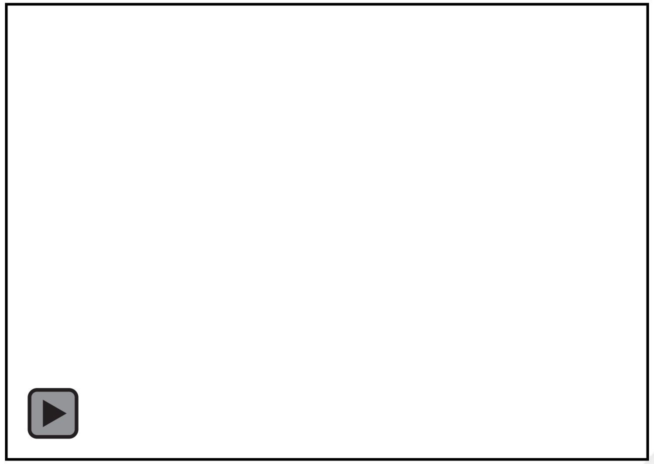
- Li-ion batteries undergoing thermal runaway produce hot combustible gases and solid particles that can heat other cells in the system
- Gases impinge directly on the surface above and travel through channels between modules, heating more distant cells.
- Heating from successive failures spreads heat through the system.



Lower module to upper module heat transfer from successive vents

Example vent impingement from experiments

Example vent impingement from simulations

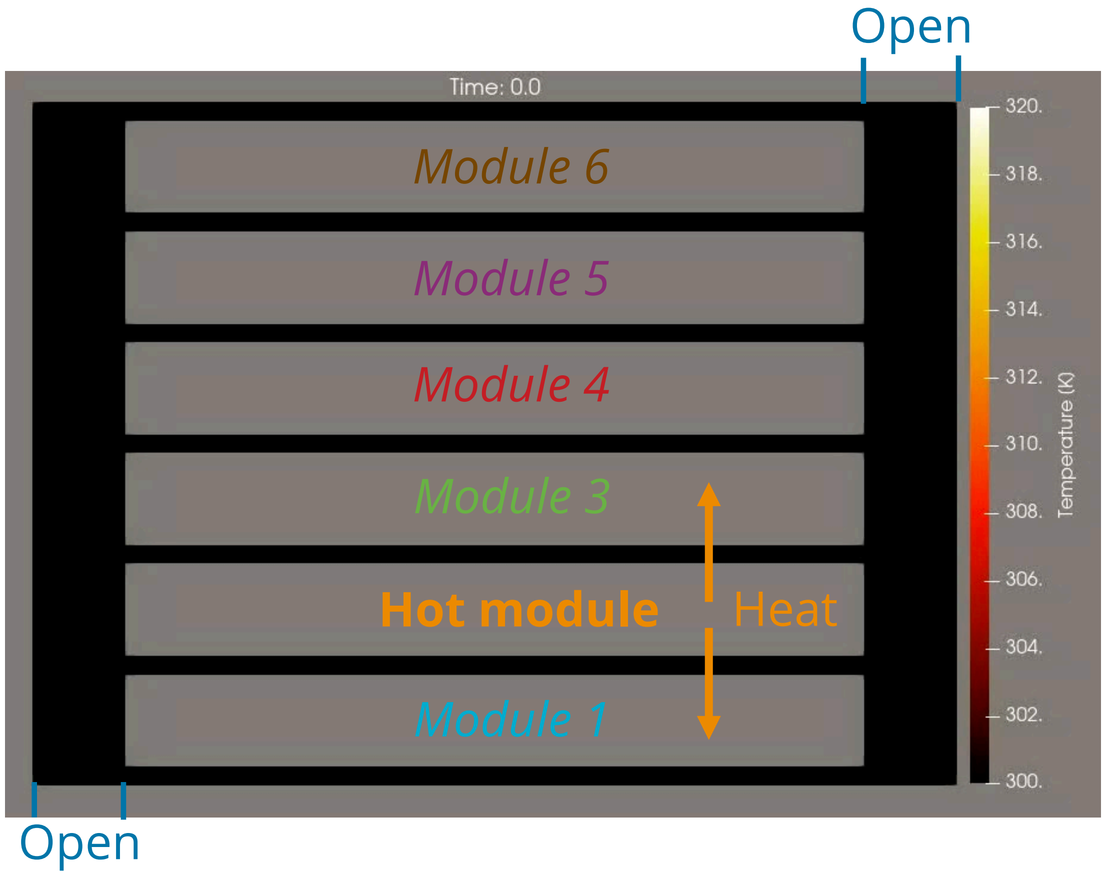


Top right done in collaboration with the University of Memphis: Qatramez et al., “The role of lithium-ion battery vent gas …” Submitted to Journal of Heat and Mass Transfer.

PASSIVE HEATING: SIMULATIONS

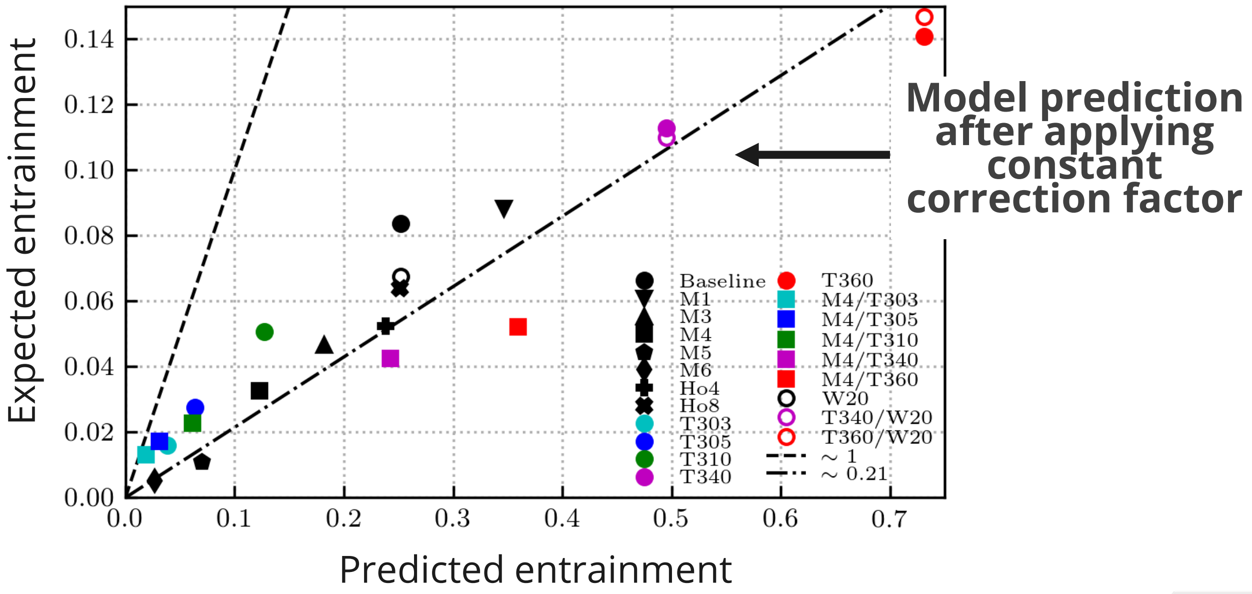
Modules generally experiment prolonged periods of elevated temperature prior to thermal runaway. Assessing heat transfer is important for preheating over other modules.

- Simulations conducted using Sandia's internal code suite Sierra/Fuego



Developed simple, algebraic model making several assumptions supported by the numerical simulation and evaluated using average temperature transport equation

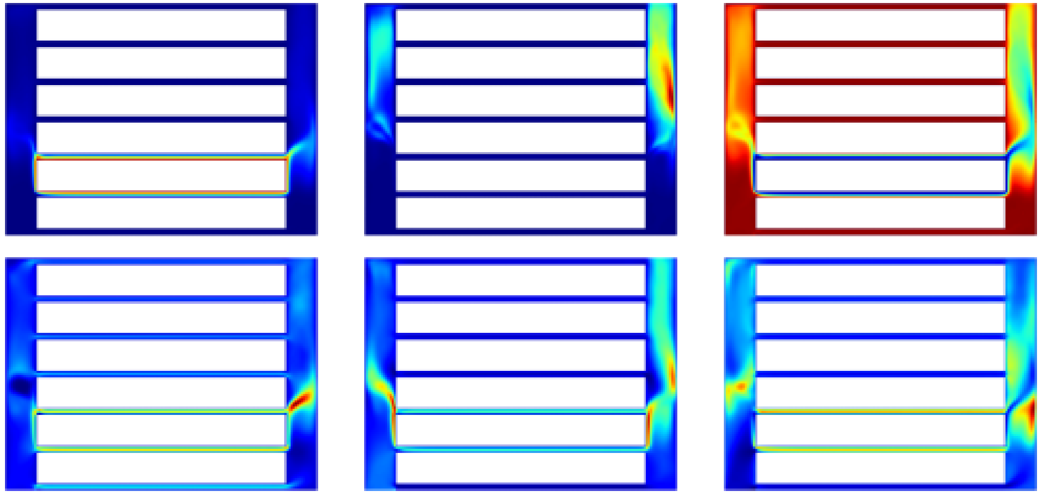
- Reduction in CPU cost: 6+ orders of magnitude



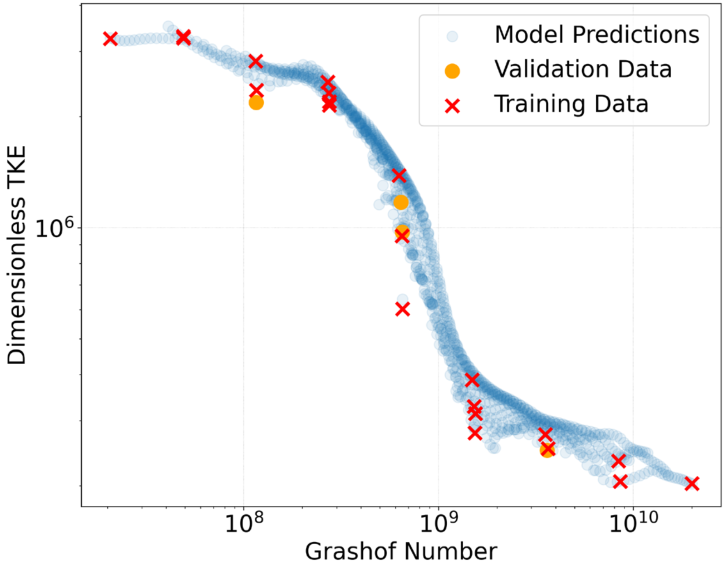
Meehan et al., *Journal of Energy Storage* 153 (2026): 120808.

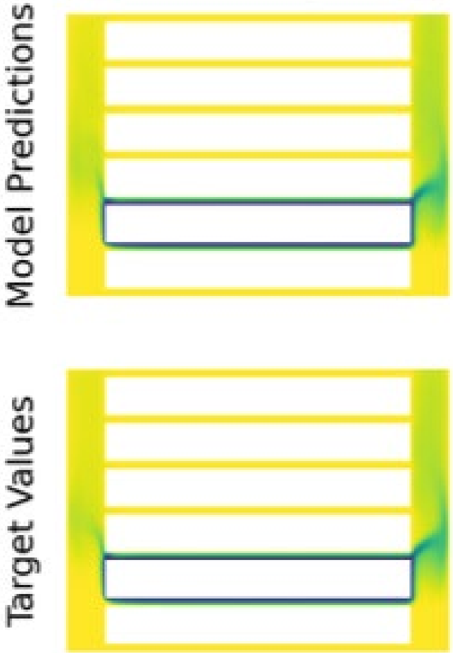
PASSIVE HEATING: MACHINE LEARNING

- Use *structure-preserving* reduced-order modeling methods to *learn* a reduced finite element basis and a nonlinear conservation law using simulation data. Creates physics-conserving model by *construction*.
- The reduced-order model can:
  - Feedback into cell-to-cell propagation (e.g., heat flux)
  - Build control algorithms for active mitigation
  - Include physics-conserving properties by construction



Reduce simulations of millions of elements to only 6 coarse elements, allows real-time evaluation speeds





Excellent accuracy shown using turbulent kinetic energy (heat transfer, left) and field reconstructions (right)

Kinch, Brooks, et al. "Structure-preserving digital twins via conditional neural whitney forms." *arXiv preprint arXiv:2508.06981* (2025).

RACK MODEL: OVERVIEW

Description: 2-D sims with Sandia's Sierra/Fuego CFD code to simulate battery venting. A RANS turbulence model and EDC combustion model are used. Statistics are taken after flow becomes (statistically) stationary.

Parameter list:

- Module width: 80 cm
- Module height: 10 cm
- Opening width: 10 cm
- Channel height: 2 cm
- Vent width: 1 cm
- Vent velocities: 1, 2, …, 25 m/s
- Vent module: 1, 3, 5
- Vent temperature: 800, 1200 K
- Air temperature: 300 K

Roughly equivalent to LFP pouch cell

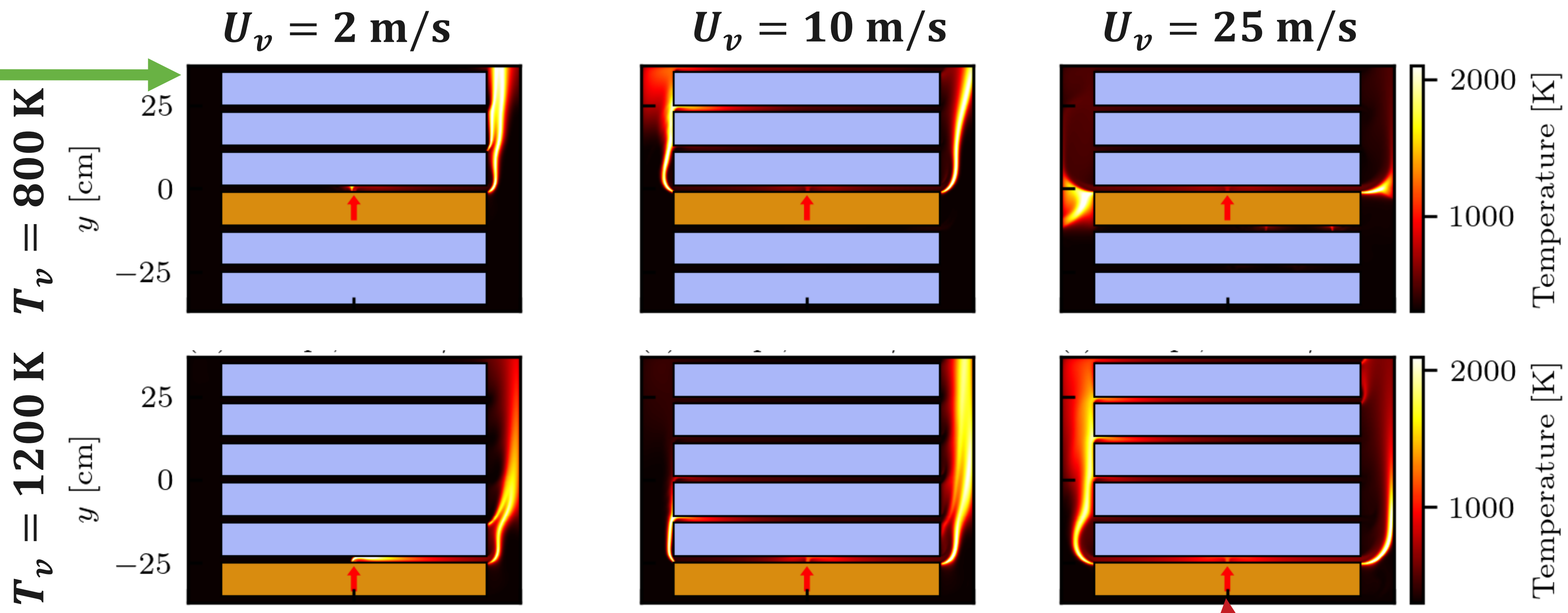
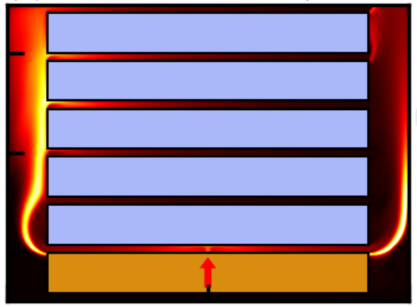


Figure showing time-average temperature fields for different vent velocities and temperatures

Approaching equivalence of NMC prismatic cell

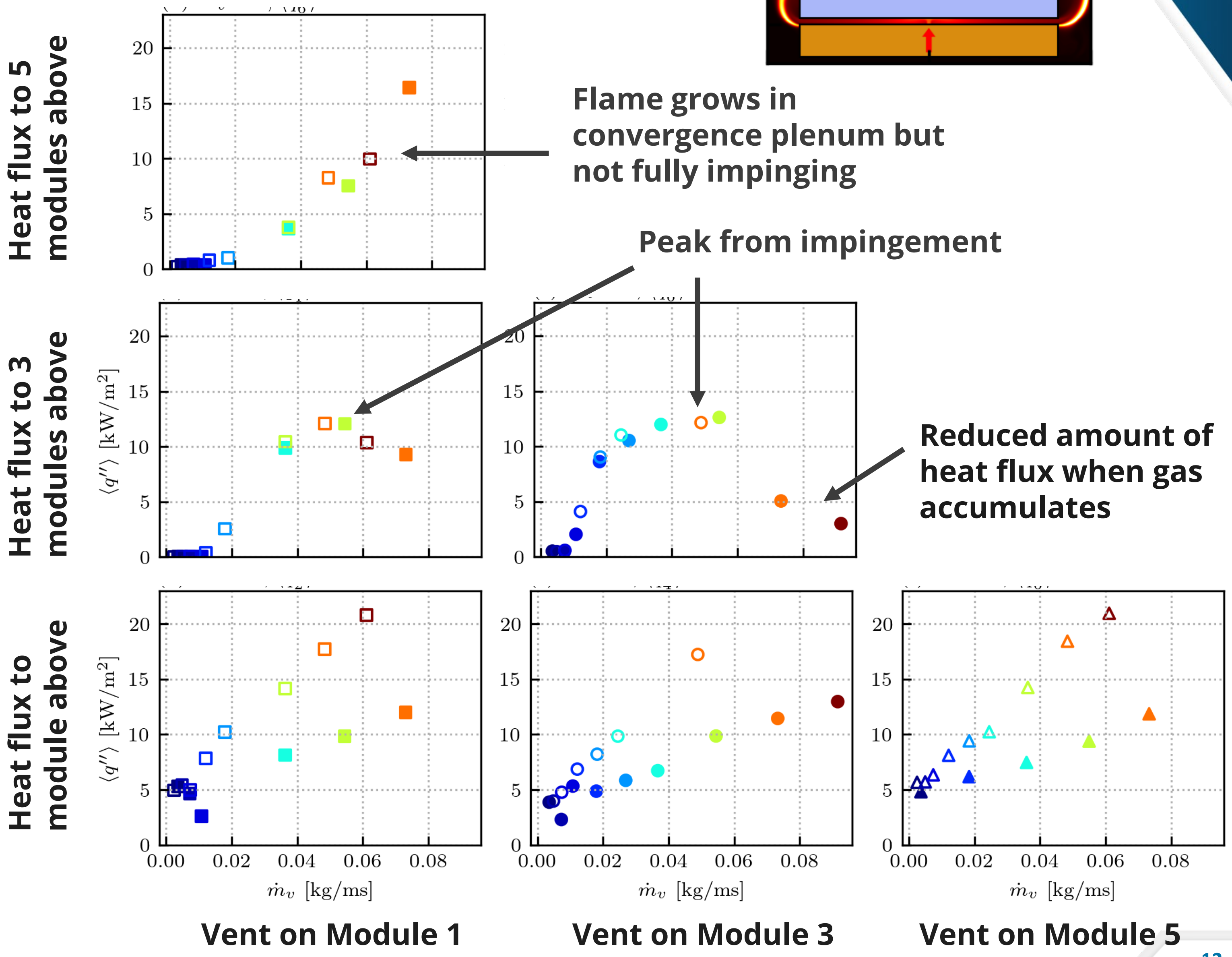
Meehan et al., Fire Safety Journal (2026): 104725.

RACK MODEL: HEAT TRANSFER



Key findings:

- Heat flux to the module above venting (bottom row) scales according to jet impingement physics
- Heat flux to non-adjacent modules peaks when flame impinges on the module and remains non-zero during hot gas accumulation.



<u>Legend for images</u>

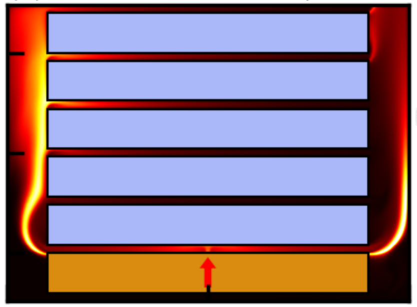
Color: blue to red = increasing velocity

Symbol: module number

Fill: open = higher vent temperature

Meehan et al., Fire Safety Journal (2026): 104725.

RACK MODEL: GAS FLOW



Key findings:

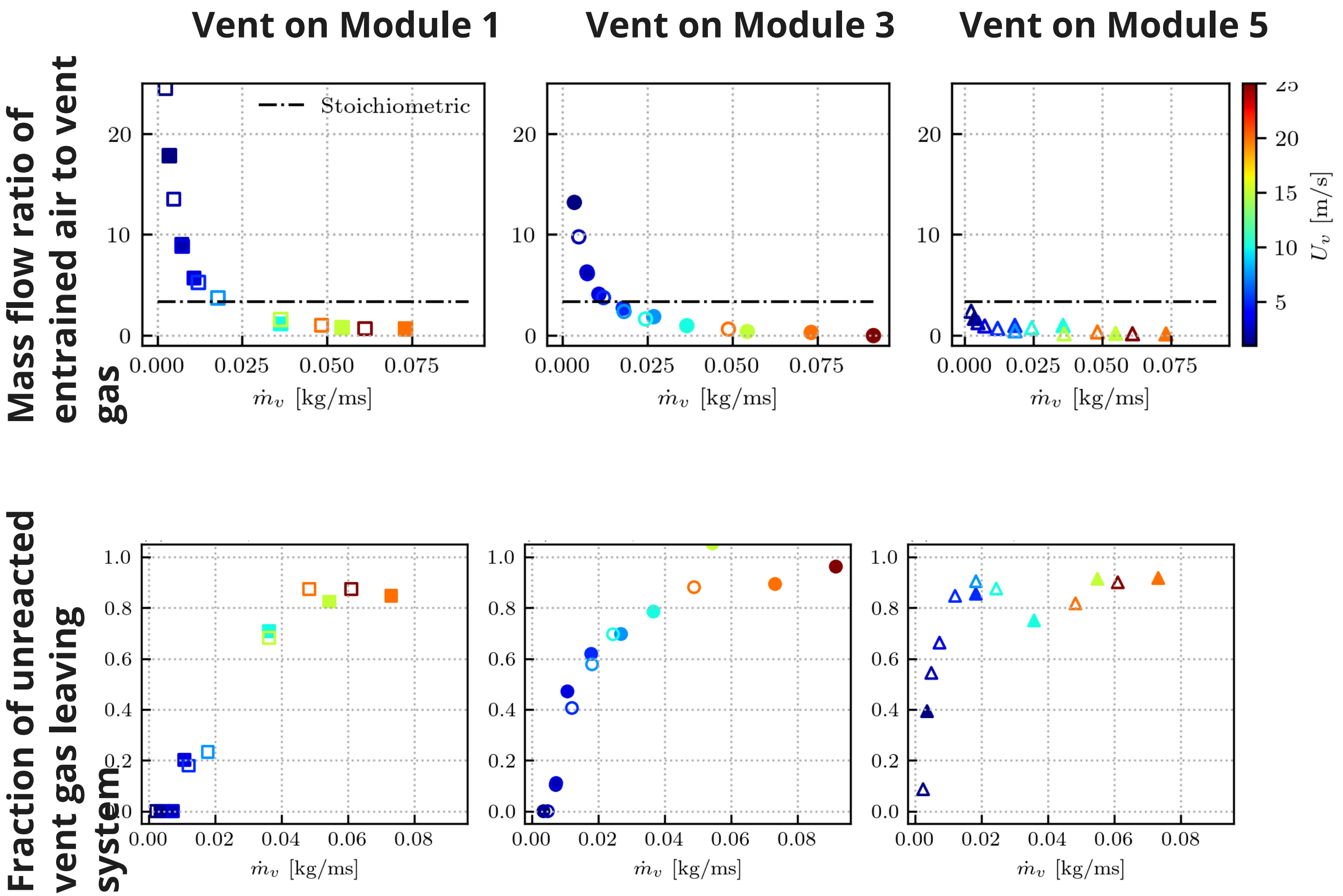
- More air entrainment when the vent is near the bottom and released slowly to generate large buoyant force relative to momentum
- Under most realistic conditions, vent gas leaves ESS unreacted. Resulting in heat release outside of rack endangering neighboring racks.
- Unreacted vent gases mixed with entrained air near stoichiometric conditions pose a greater ignition/deflagration hazard.

<ins>Legend for images</ins>

Color: blue to red = increasing velocity

Symbol: module number

Fill: open = higher vent temperature



Meehan et al., Fire Safety Journal (2026): 104725.

SUMMARY, IMPACT, AND FUTURE DIRECTION

Summary:

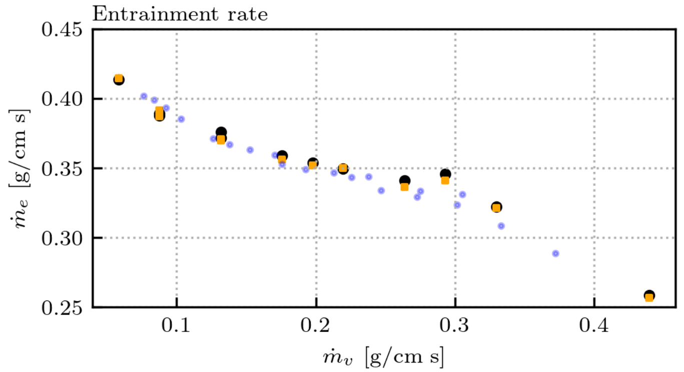
- Built upon small-scale aspects of the thermal runaway problem to design relevant rack-scale simulations
- Improved understanding on the fundamental aspects that contribute the module-to-module propagation

Impact:

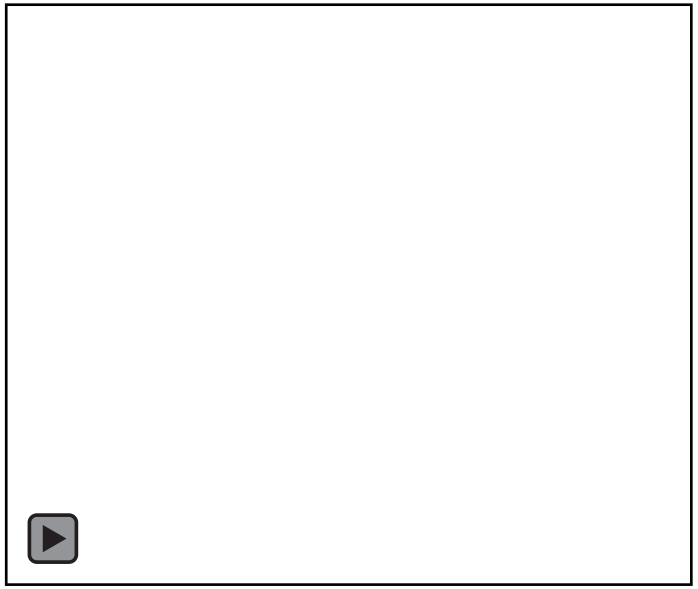
- Identified methods to construct fast-running models to improve design optimization or control strategies to reduce likelihood of thermal runaway propagation

Future direction:

- Transition idealized models to more closely resemble real ESSs
- Develop ML framework further to improve applicability during venting and generalizability across geometries
- Couple ML with classic finite element models to replace computationally-expensive components



Example calculations of entrainment comparing ML approach (blue/orange) with CFD (black) for venting cases



Exploration of the parameter space using ML model of battery venting

ACKNOWLEDGEMENTS

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