UNDERSTANDING HEAT TRANSFER AND FIRE SPREAD WITHIN AN ESS RACK UNDER THERMAL RUNAWAY CONDITIONS

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PROJECT PROFILE
Topic/Vertical: Safety & Reliability Strategic Pathway: **Stabilize:** Addressing urgent needs to ensure safety, reliability, and system security Project start and finish: FY25-FY26

PROBLEM AND OBJECTIVE

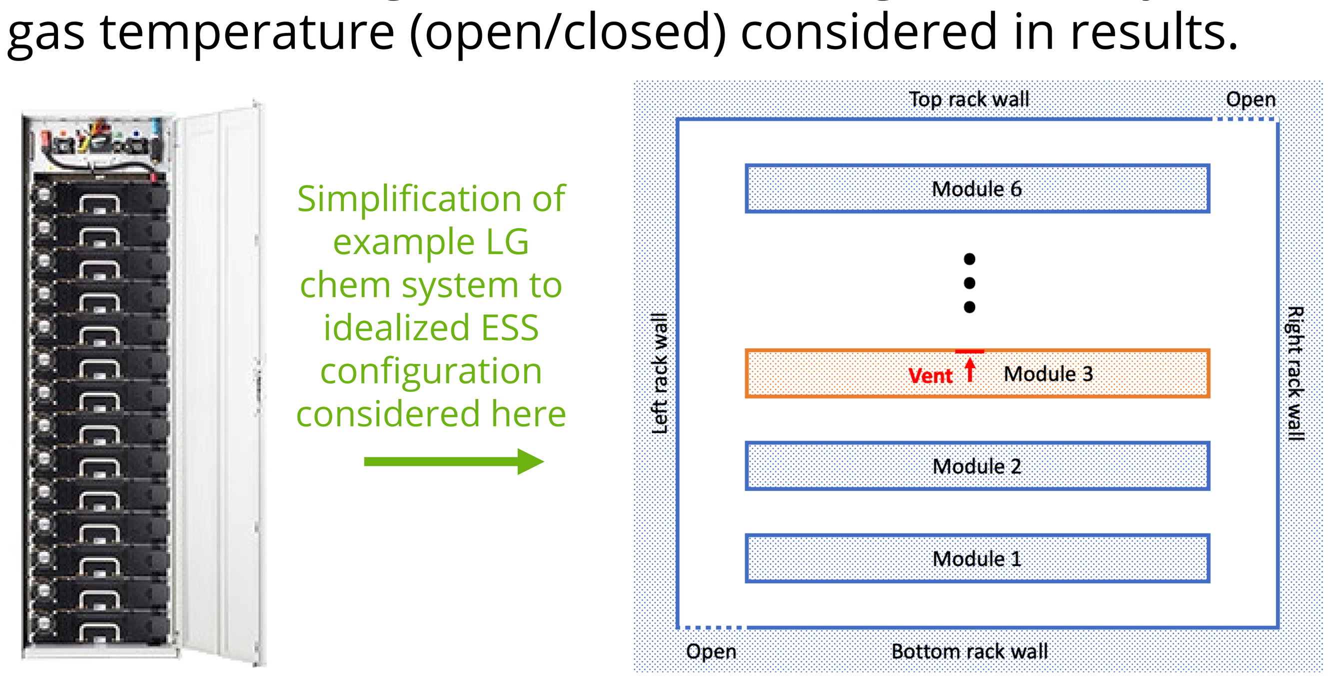
Li-ion batteries in thermal runaway produce hot flammable gases that can spread fires externally and within an ESS rack.

- ESS systems can be designed to resist propagation, but the location of combusting gases must be understood.
- Gas generation is roughly 100x the cell volume that has gone into runaway, so rich mixtures may form in confined spaces.
- Air entrainment into rack will allow in-rack combustion and faster thermal runaway spread within the rack.
- Alternatively, reduced air entrainment leads to potential rack-to-rack spread with external fire.
- Difficult to predict entrainment with momentum-driven venting and buoyant plume rise through confined space.

APPROACH

Using Sandia's Sierra/Fuego code to predict venting and in-rack burning for generic Energy Storage System (ESS) rack.

- Simplified modules in 2-D domain with entrainment from bottom left and flow out the top right.
- Considering steady vent inflow of $H_2/CO/CO_2/CH_4$ mixture; Reynolds-averaged Navier-Stokes; k-ϵ turbulence model; EDC combustion model, discrete ordinates radiative transport (Thurgood 4th order quadrature)
- Effects of venting rate (colors), venting module (symbols), gas temperature (open/closed) considered in results.



FUTURE DIRECTIONS

- Machine learning of flow for digital-twin model development [1]:
  - Refine understanding of parameter space using fast running model to improve design decisions
  - Allow the BMS to interpret and respond to abnormal scenarios [2]
- Transition generic ESS model to be more application specific

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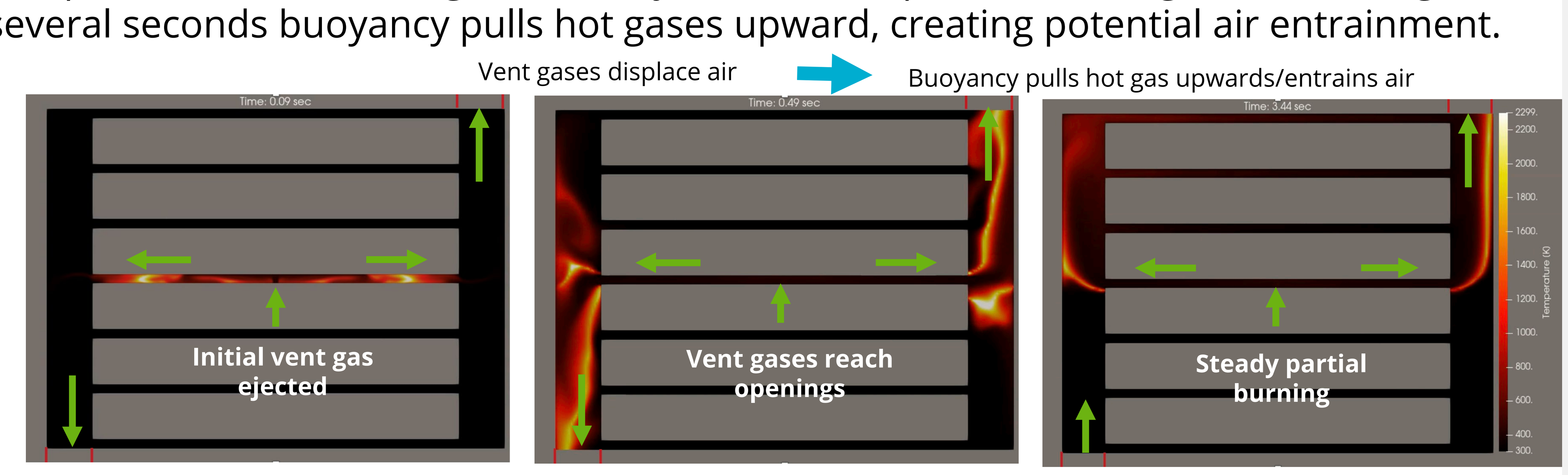
Temporal evolution: Vent gases are injected and displace air during initial burning. After several seconds buoyancy pulls hot gases upward, creating potential air entrainment.

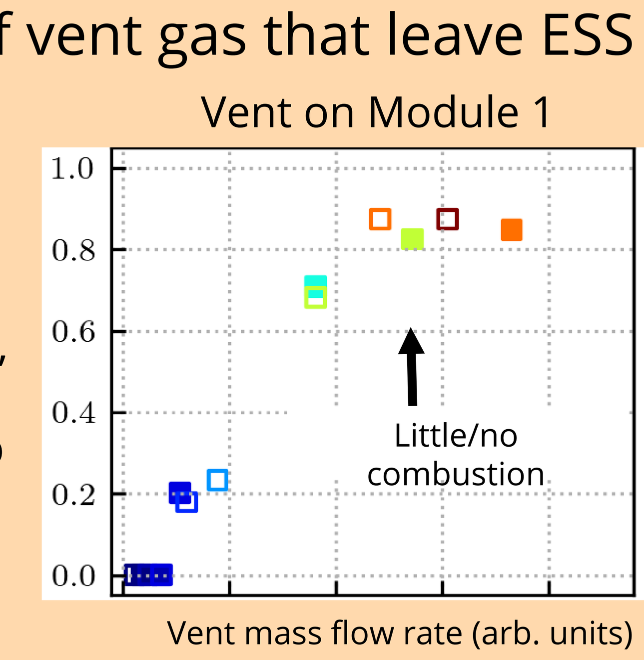


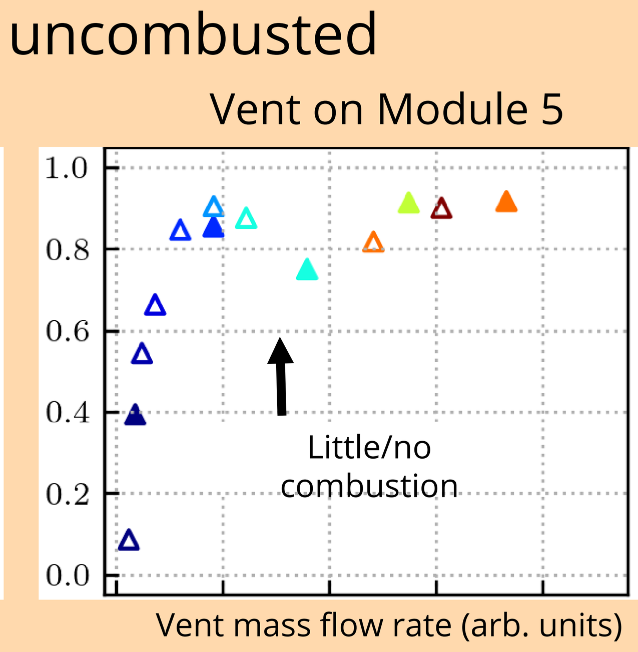
RESULTS

- When vent is near the bottom of the ESS, buoyant entrainment of air is enhanced, and more vent gases burn within the rack [3].
- Buoyant entrainment is resisted by momentum from strong venting.
- As vent mass flow rate increases or when venting occurs closer to the top, combustion is suppressed and flammable gases escape [4].

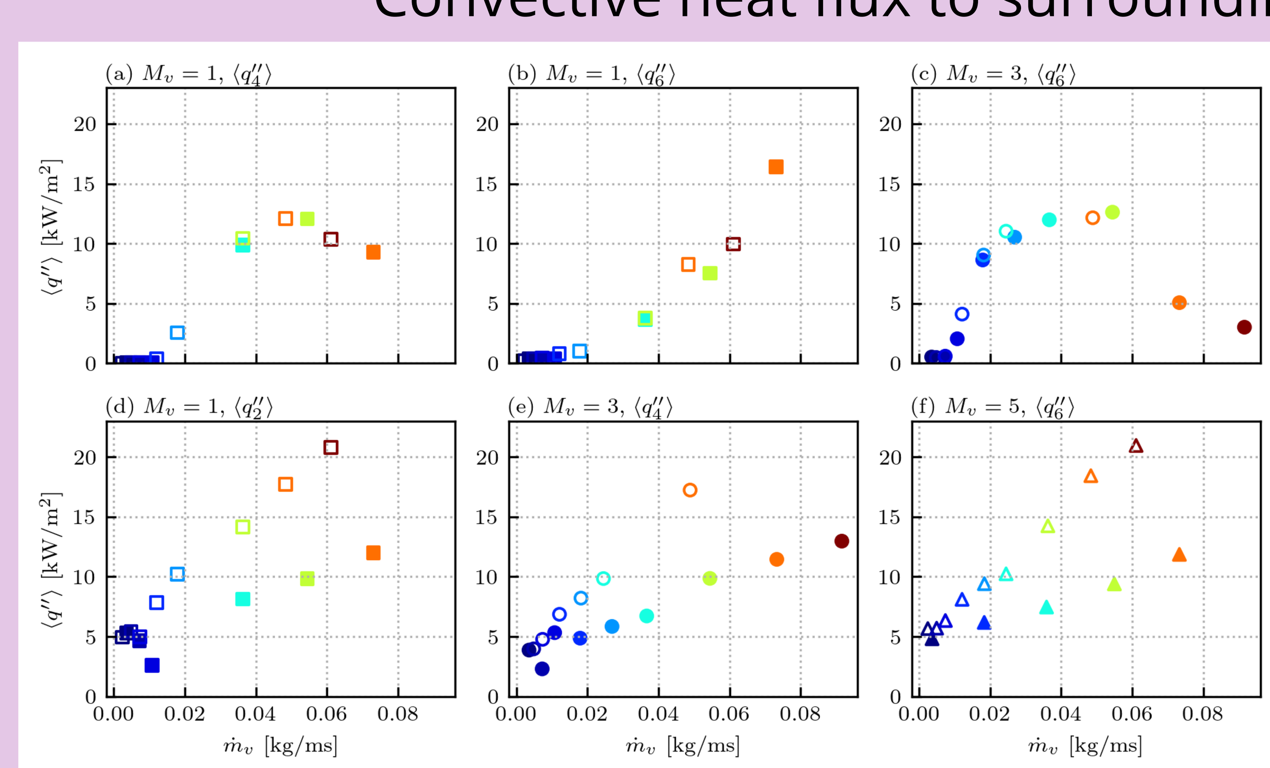
Fraction of vent gas that leave ESS uncombusted

- When vent is near bottom of rack, and mass flow rate is small, all vent gas combusts within the ESS.
- As mass flow rate increases, combustion is suppressed.
- When the vent is nearer top of the ESS, combustion is suppressed at lower mass flow rates of the vent [4].





Convective heat flux to surrounding modules



- Surface-averaged heat flux to non-adjacent module (module far from venting) shown in the top row peaks when flame impinges on the module and remains above zero after flame suppression
- Heat flux to adjacent module (module just above venting) shown in the bottom row scales with known jet impingement physics [4].

Symbols: square/circle/triangle – vent on Mod 1/3/5;
Color – vent velocity (blue – slow → red – fast);
Closed/Open – vent temperature 800/1200K

CONCLUSIONS & IMPACT

Predictions demonstrate the scaling of the buoyant flow to entrain air into an ESS rack where combustion might occur. Under many rapid venting scenarios (i.e., larger cells or multiple simultaneous thermal runaway event), venting is strong enough to displace air and prevent entrainment.

- In-rack combustion might accelerate module-to-module propagation.
- Flammable gases that leave rack might present explosion hazard if not ignited or could contribute to larger-scale fire spread.

References

[1] Kinch et al. arXiv preprint arXiv:2508.06981 (2025).
[2] Mueller, et al., IEEE, ECCE (2022) and Mueller, et al., US 11,855,264, U.S. Patent & Trademark Off., Dec. 2023.
[3] Meehan et al., Journal of Energy Storage 153 (2026): 120808.
[4] Meehan et al., Fire Safety Journal (2026): 104725.

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