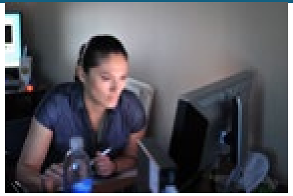
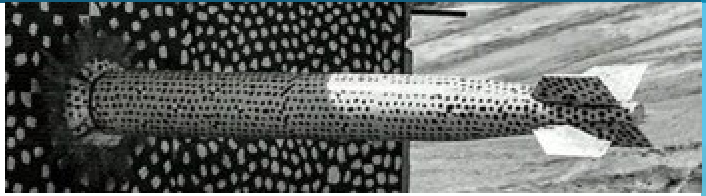
Energy Redistribution as a Method for Mitigating Risk of Propagating Thermal Runaway

PRESENTED BY

Jake Mueller

Project Team: Yuliya Preger, Andrew Kurzawski, Luciano Garcia Rodriguez, John Hewson
DOE Office of Electricity Energy Storage Program Peer Review
October 11-13, 2022
Presentation ID: 802

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND2022-13244 C

Utility-Scale Storage System Failures

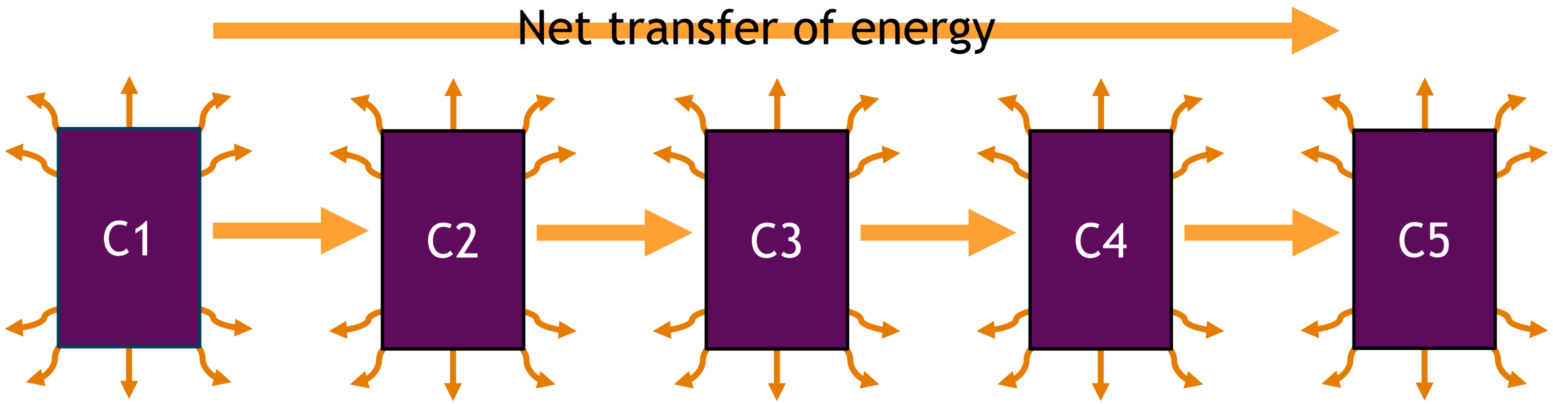
EPRI BESS Failure Database
https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database

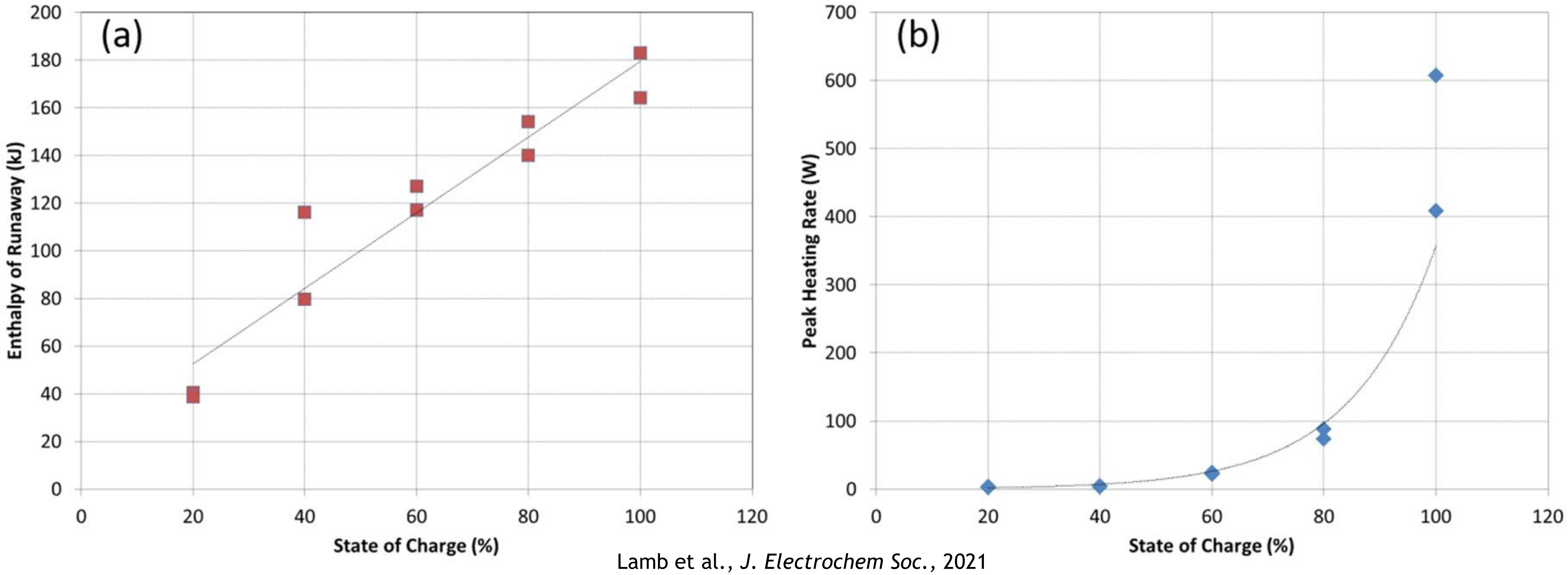
Factors Influencing Thermal Runaway

What determines the severity of a thermal runaway event?

- Amount of energy released (enthalpy of runaway)
- Rate at which energy is released

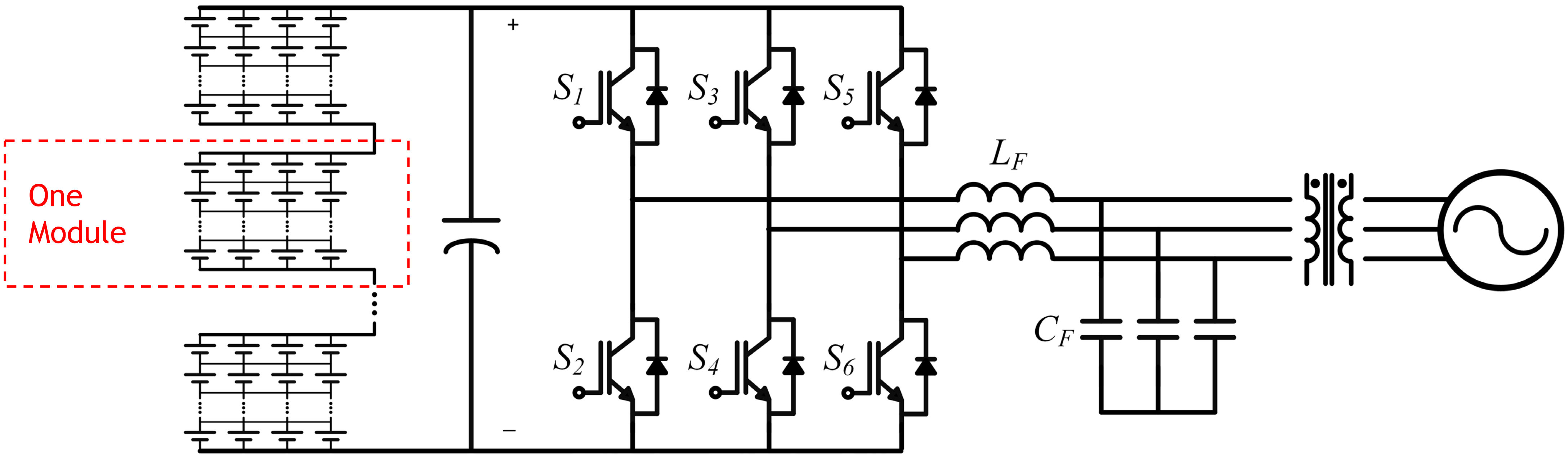
Both depend on state of charge



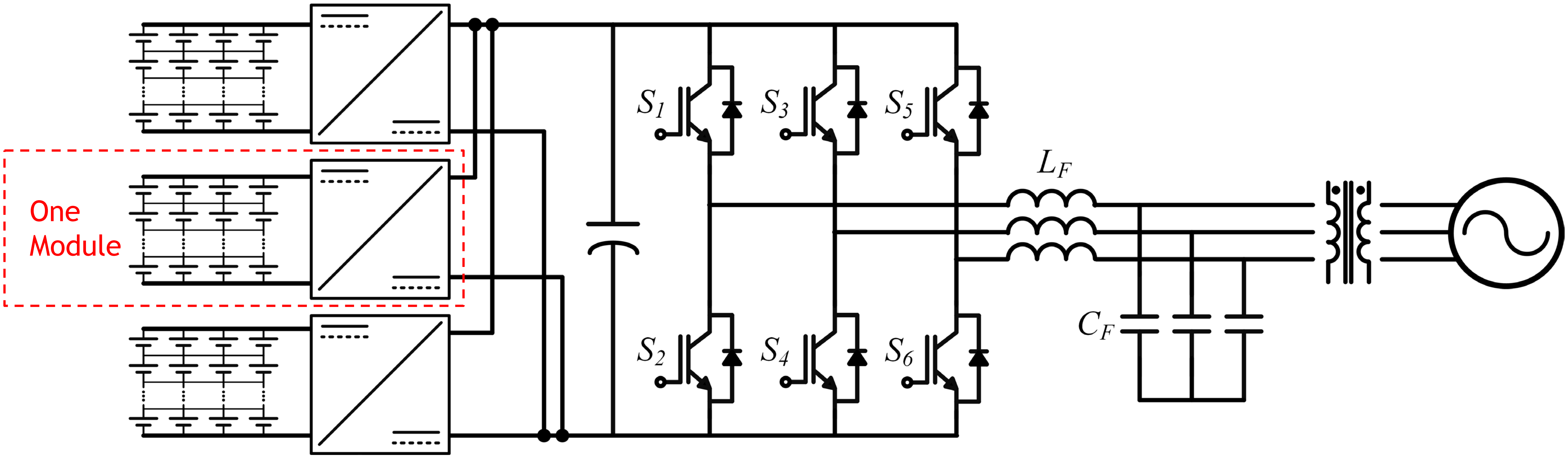


Lamb et al., *J. Electrochem Soc.*, 2021

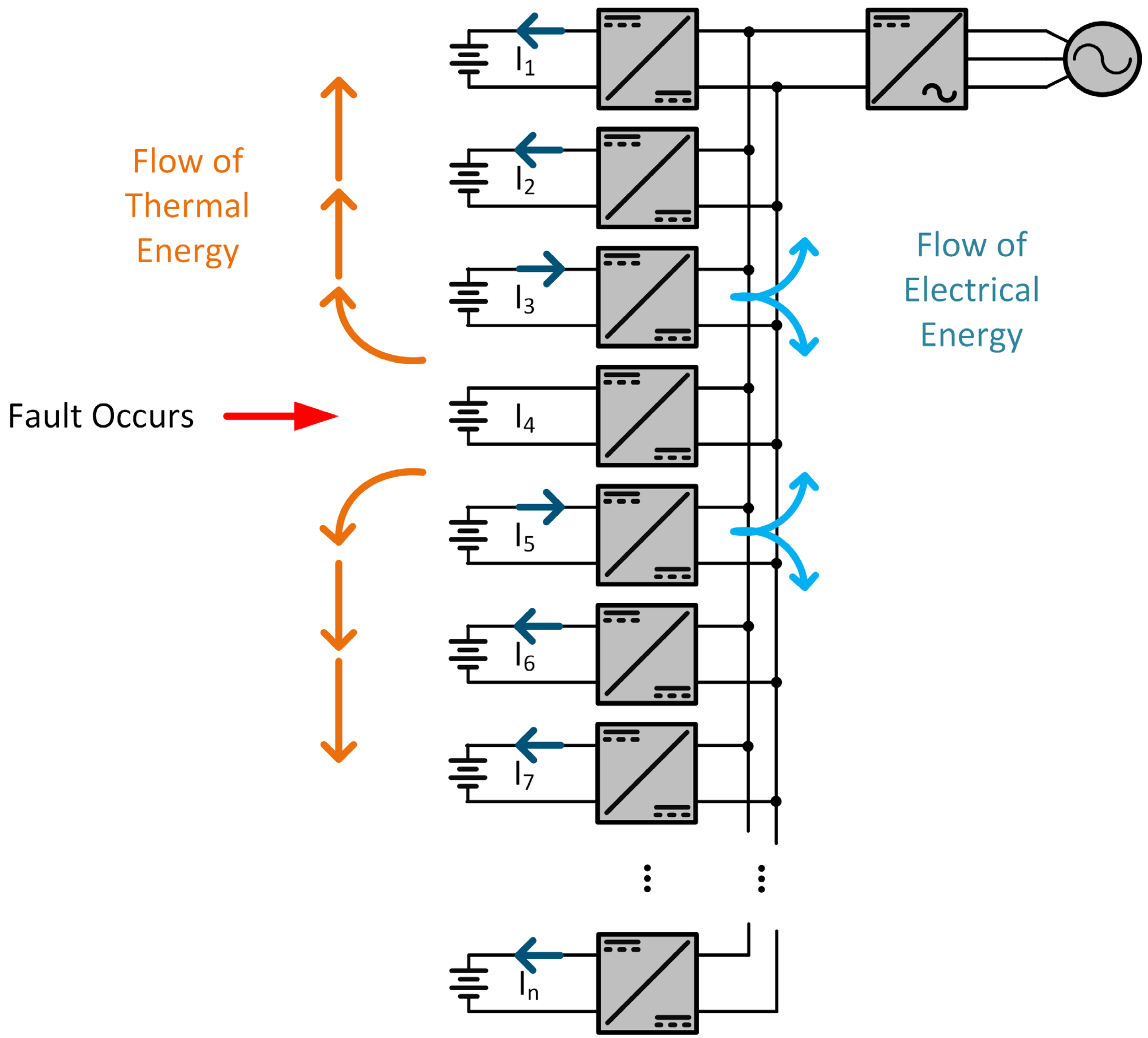
Conventional Power Conversion System



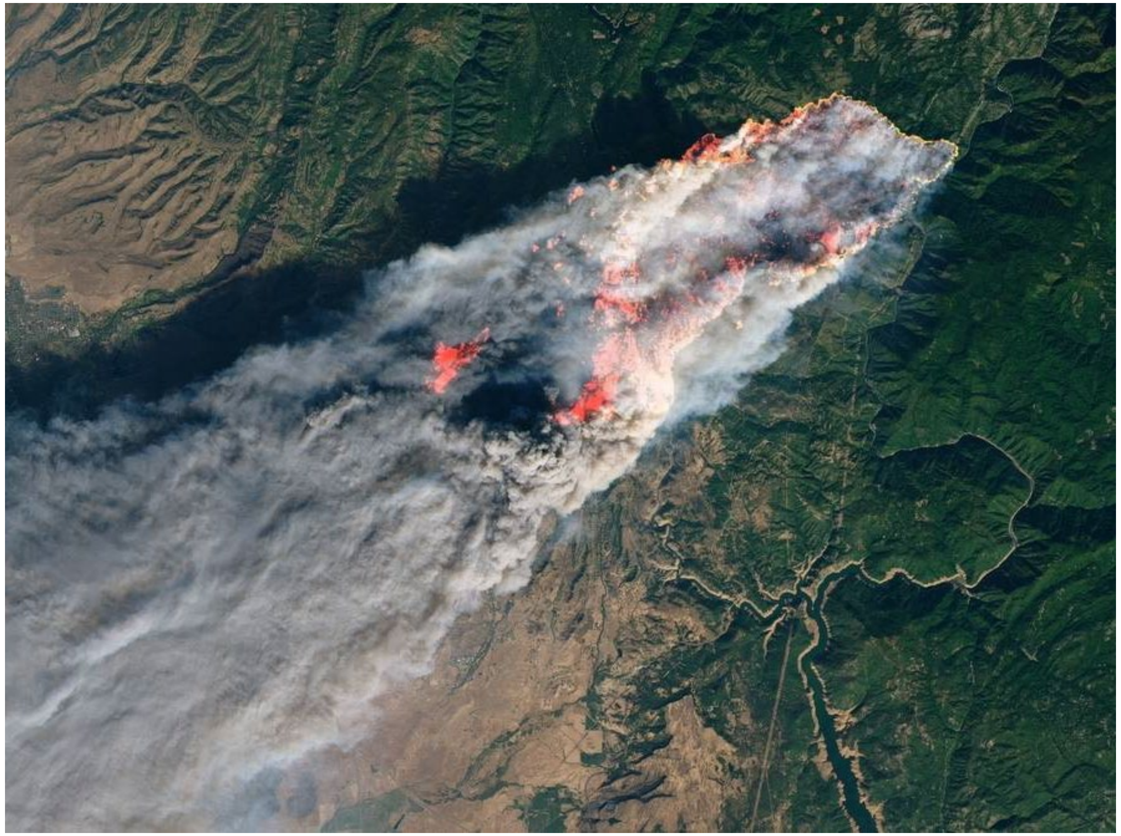
Multi-Stage Power Conversion System



Energy Redistribution



Wildfire Analogy



Propagation of a wildfire front depends on fuel

A firebreak is formed by removing the available fuel in the pathway of the fire

Where do you put the firebreak?

How wide does it need to be?

How much time do you have to respond?

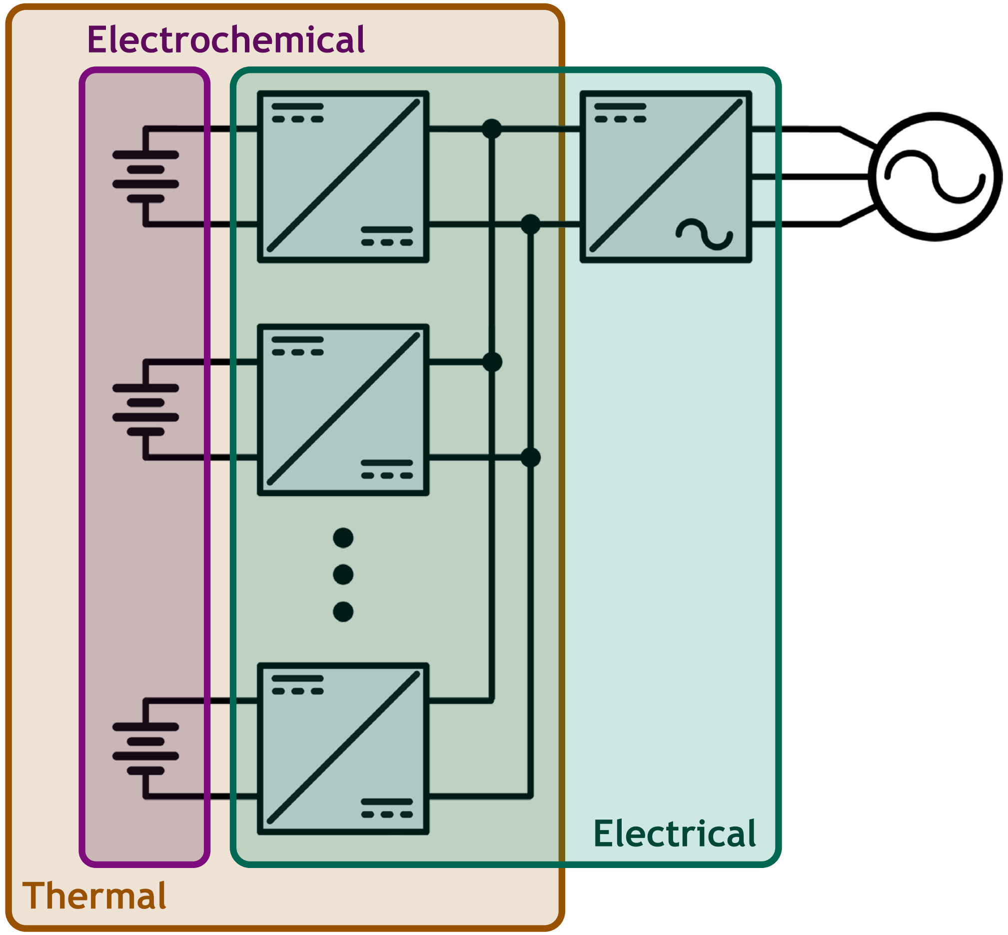
System-Level Simulation Studies

System Under Consideration

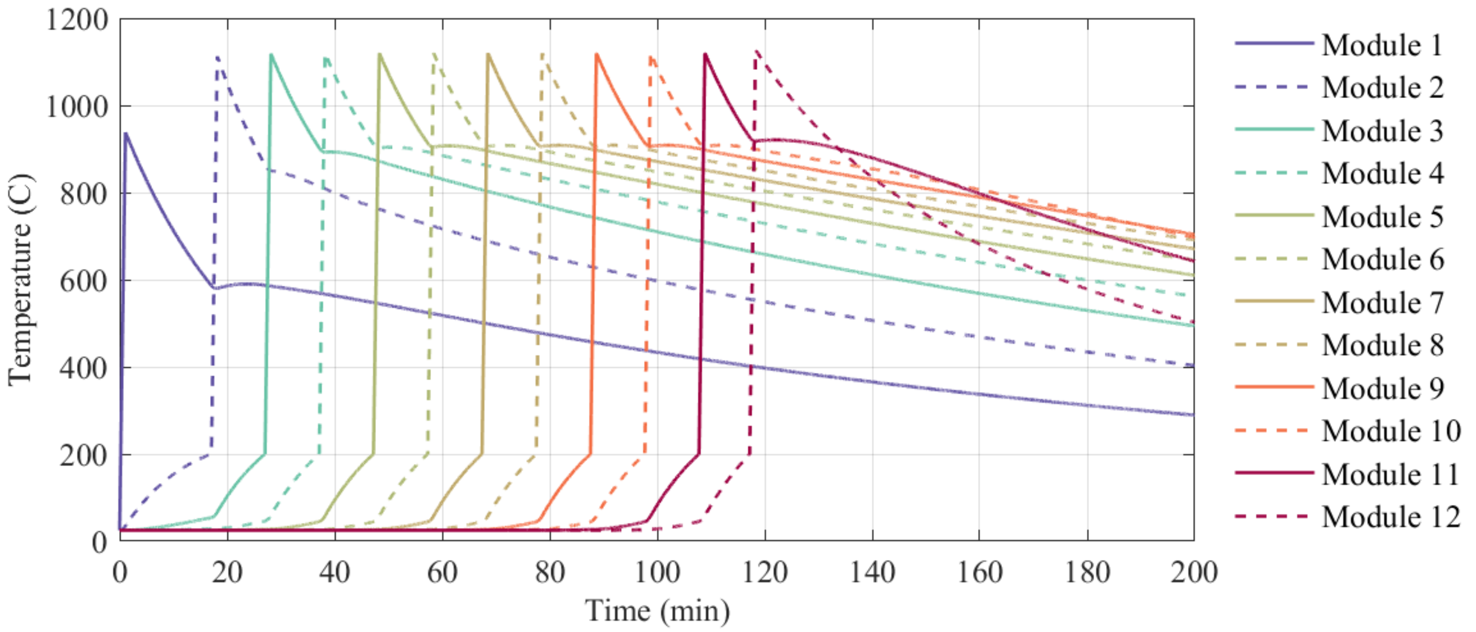
- 160kW/80kWh system organized into 12x rack-mount modules
- Each module consists of storage devices and a DC-DC converter, modules connect in parallel to common DC bus
- Storage modules
  - Rated power/energy 13.2kW/6.6kWh
  - Module capacity 128Ah, nominal voltage 52V
  - Capable of 2C continuous discharge
- DC-DC converters
  - Modeled as bidirectional buck converters for simplicity
  - Power/voltage ratings matched to storage modules
  - Converters fail when temperatures exceed 125° C

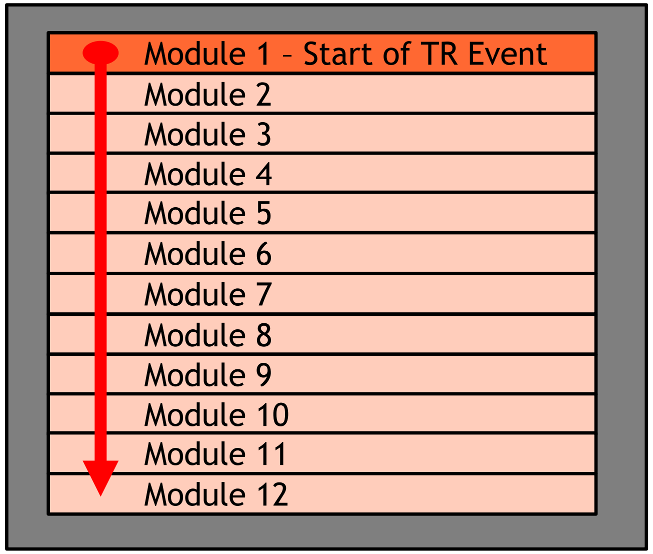
Modeling Thermal Behavior

- Thermal runaway triggered at module-level when temperature exceeds a predetermined threshold (200° C in current implementation)
- Amount of energy released and rate of energy release is a function of module SOC at time of failure
- Heat transfer between modules modeled with a linear thermal network
  - Thermal conductance is symmetric between all adjacent modules
  - Thermal conductance to ambient higher for edge modules, but otherwise equal for all modules



Case I – Propagation with No Intervention

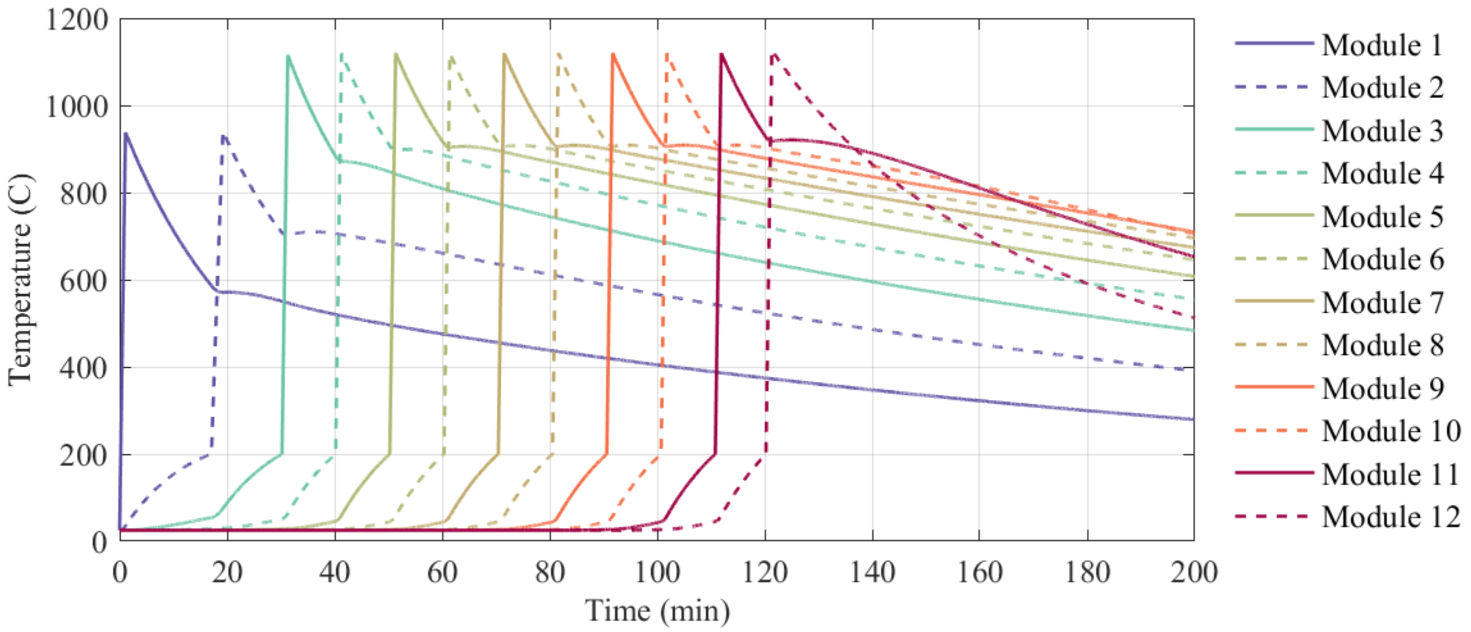


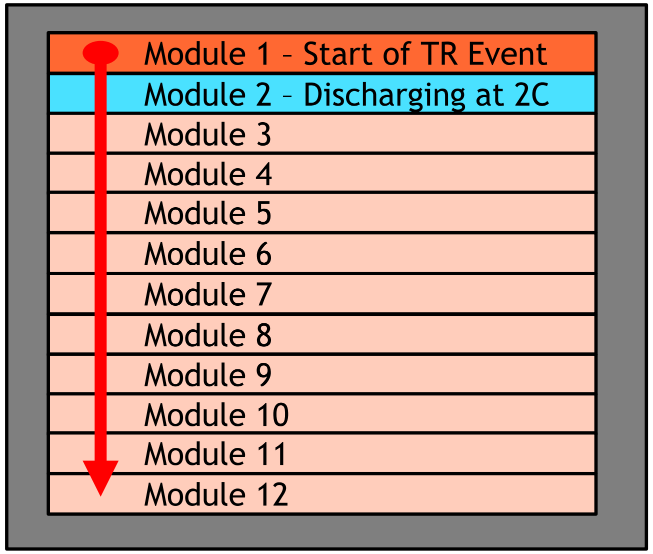


No Intervention

- Thermal runaway initiated in **module 1** at t = 0s
- All modules are at 97.5% SOC at time of initial failure
- No attempt made to mitigate propagation; all converters idle
- Edge module failures are easiest to visualize (only one direction of propagation), but model overpredicts the severity of these failure events due to semi-insulating boundary conditions

Case 2 – Intervention at Adjacent Module

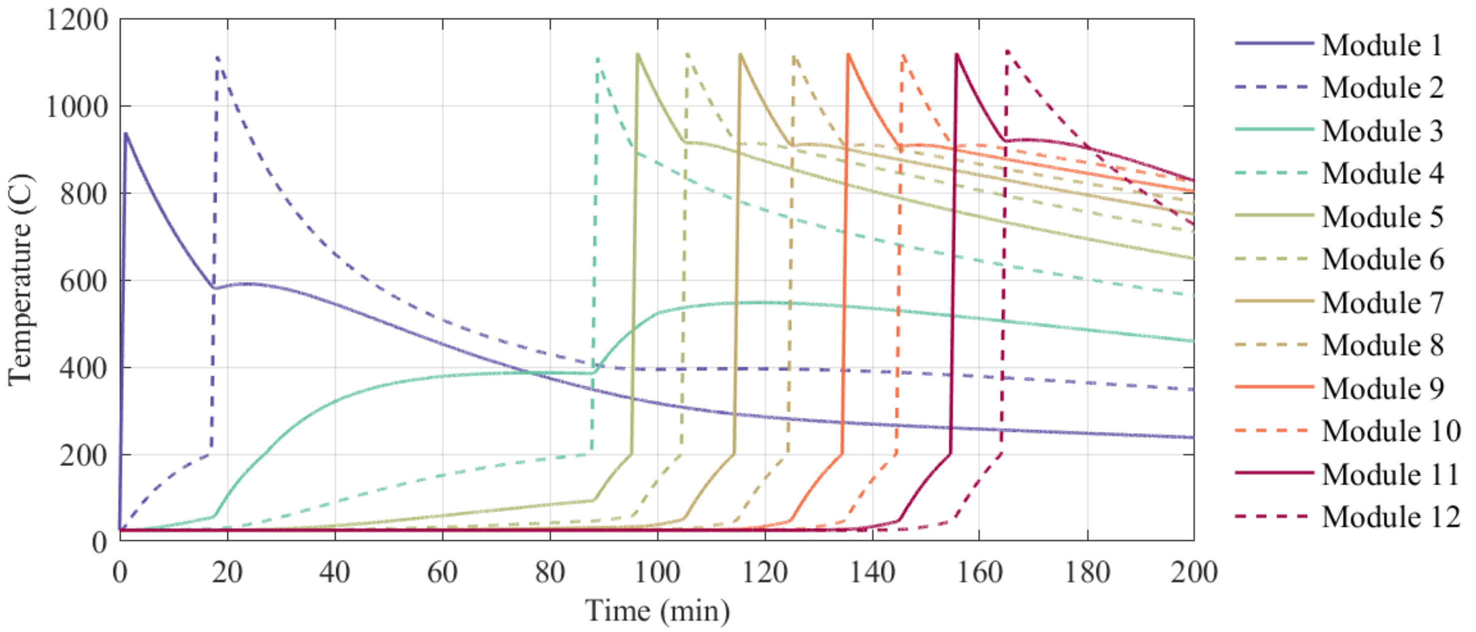


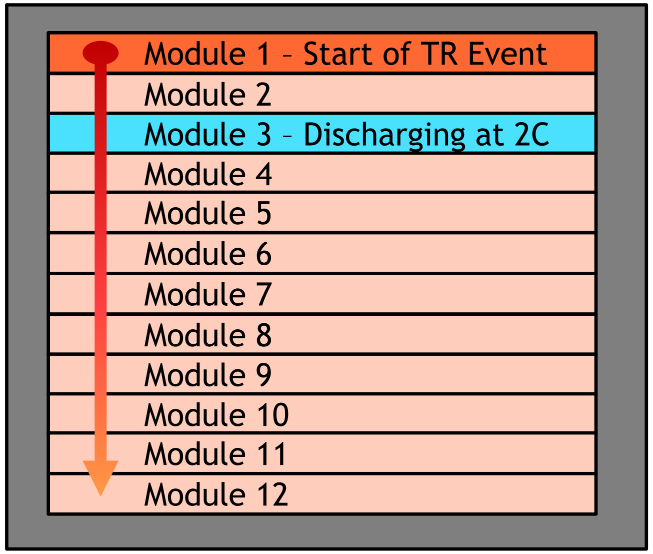


Failure – Propagation is Uninhibited

- System attempts to deplete **module 2** at discharge rate of 2C
- Module 2 temperature exceeds 100° C at ~5 min, only enough time to discharge to 81% SOC
- This level of discharge is not sufficient to obstruct propagation of thermal runaway

Case 3 – Intervention at Second Adjacent Module

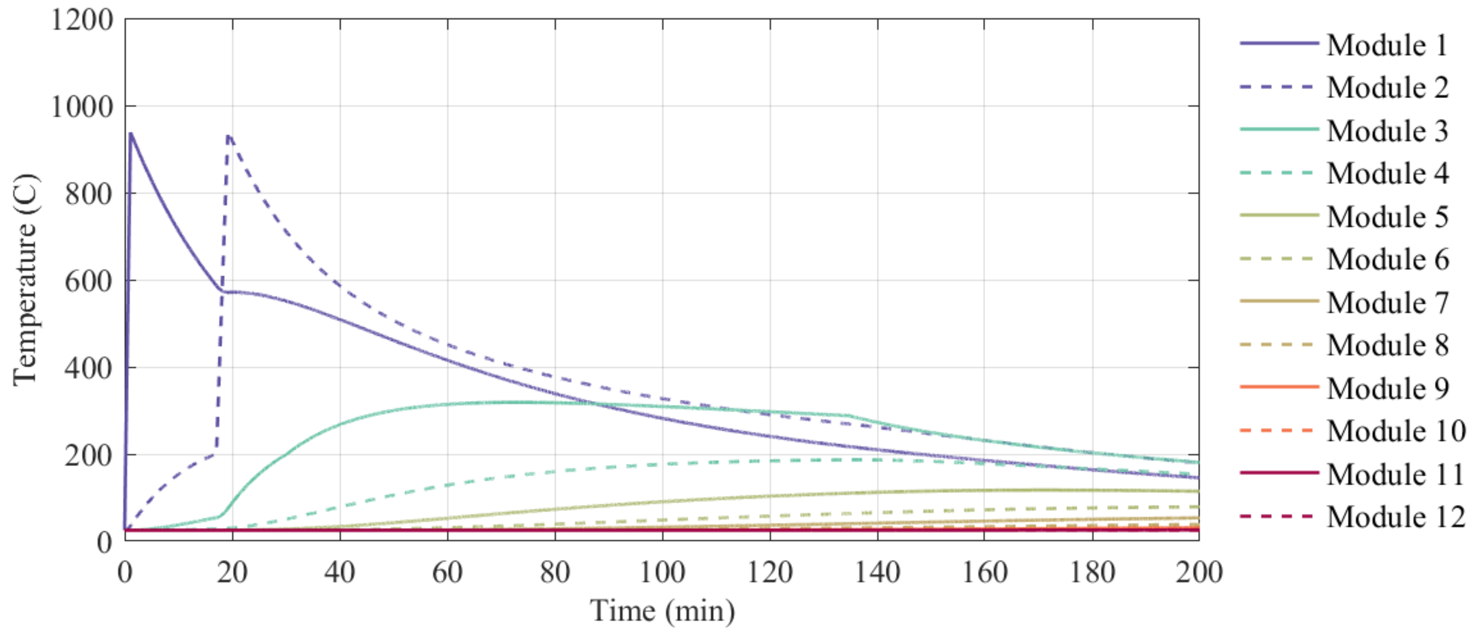


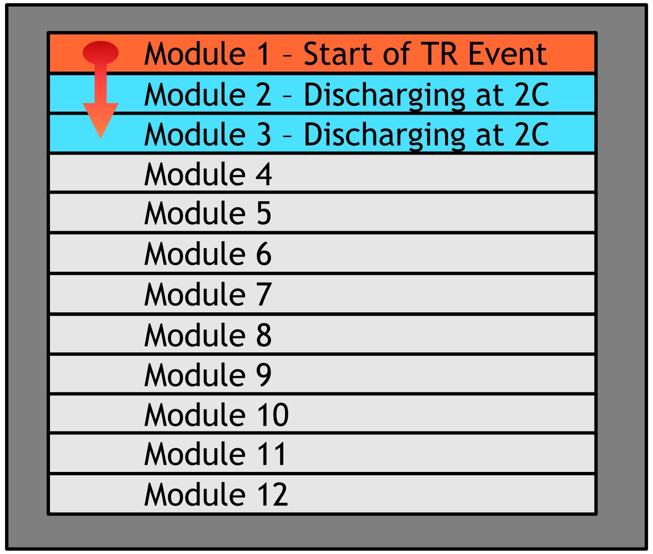


Partial Success – Propagation is Delayed

- System attempts to deplete **module 3** at discharge rate of 2C
- Module 3 temperature exceeds 100° C at ~21 min, long enough to discharge to 32% SOC
- Module 3 enters thermal runaway at about 27 min
- Propagation between modules 3 and 4 takes ~60 min (compare with <10 min in previous cases)

Case 4 – Intervention at First and Second Adjacent Modules



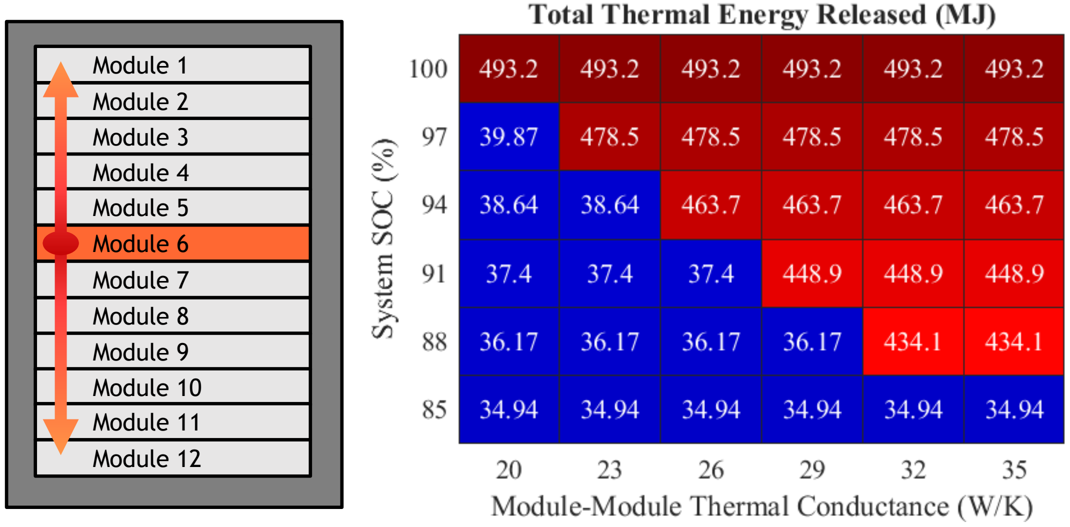


Success – Propagation is Arrested

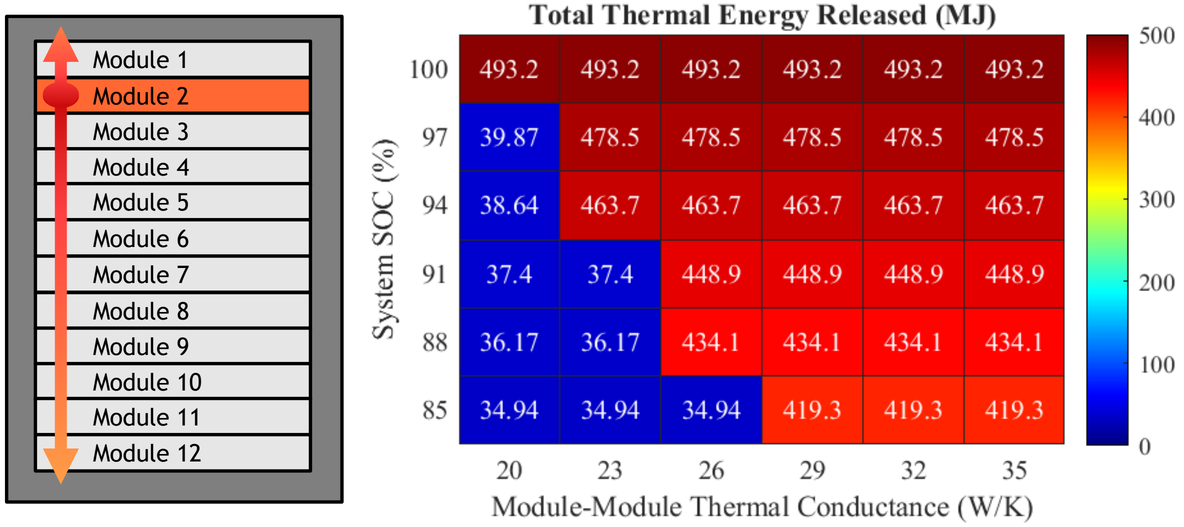
- System attempts to deplete **modules 2 and 3** at discharge rate of 2C
- Module 2 exceeds 100° C at 5 min, enters thermal runaway at 17 min with 81% SOC
- Module 3 exceeds 100° C at 21 min, enters thermal runaway at 30 min with 31% SOC
- Thermal runaway does not propagate between modules 3 and 4
- Total thermal energy release is 16.6% of no response case, 10.1% if energy from module 1 is excluded

Total Energy Release vs SOC, Thermal Conductance

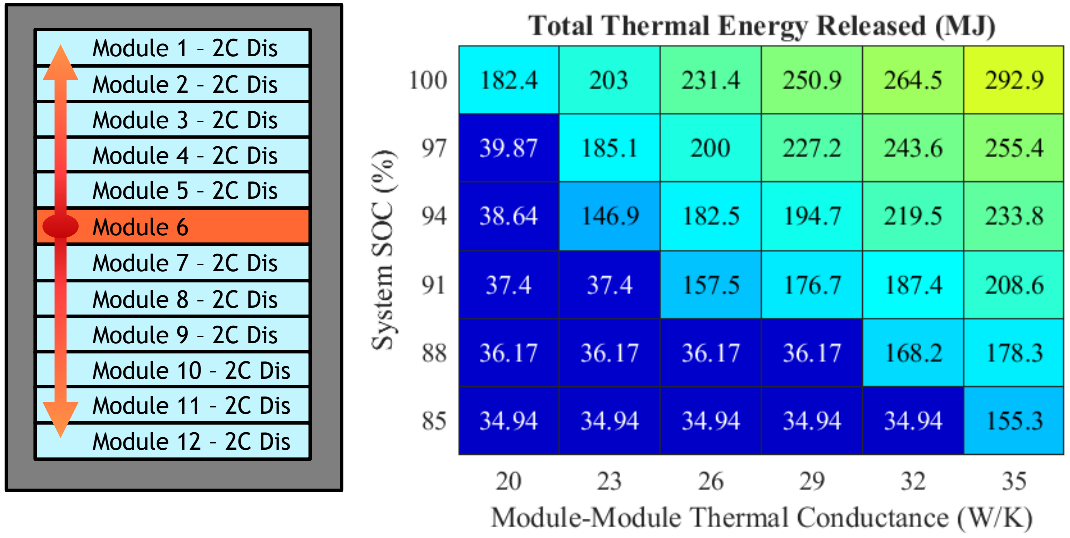
Module 6 Failure without Intervention



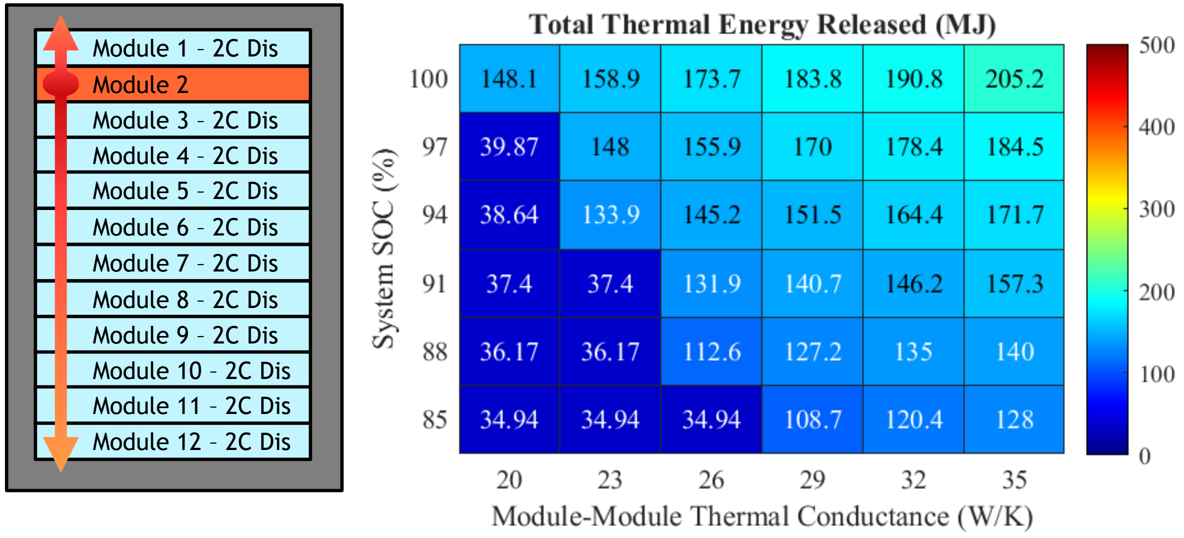
Module 2 Failure without Intervention



Module 6 Failure with Intervention



Module 2 Failure with Intervention

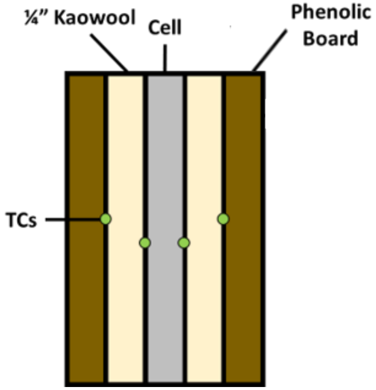


Model Refinements: Heat Generation During Rapid Discharge

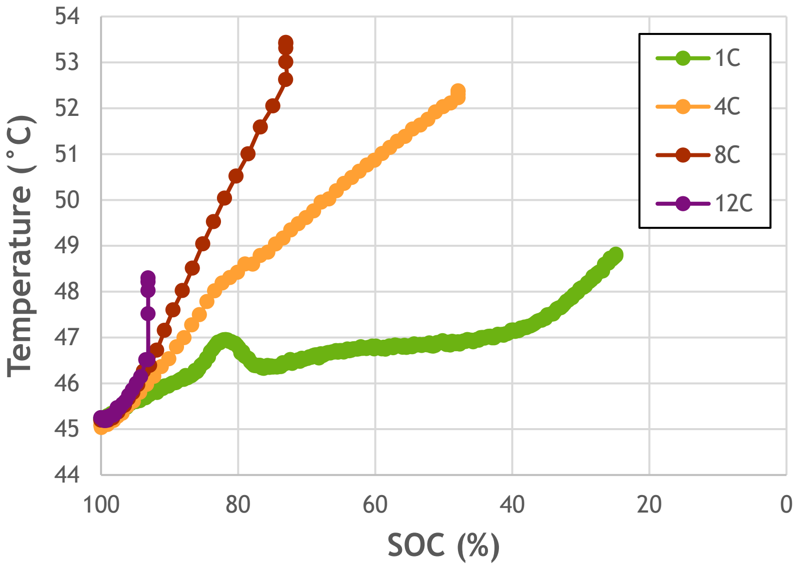
Will rapidly discharging cells generate sufficient heat to push them into thermal runaway?
How much pre-heating can be expected due to rapid discharge?

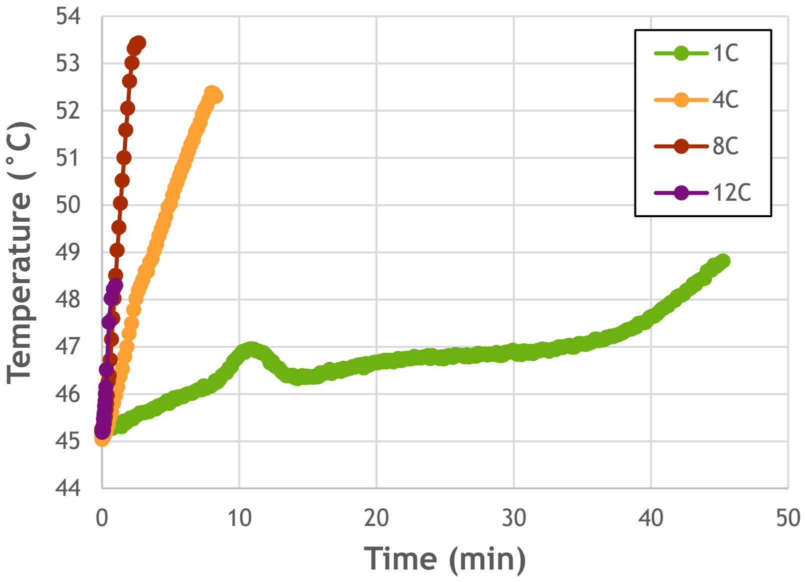
Approach:

- Measure temperature rise for different discharge rates and initial temperature conditions
- Describe heating as a function of both discharge rate and SOC



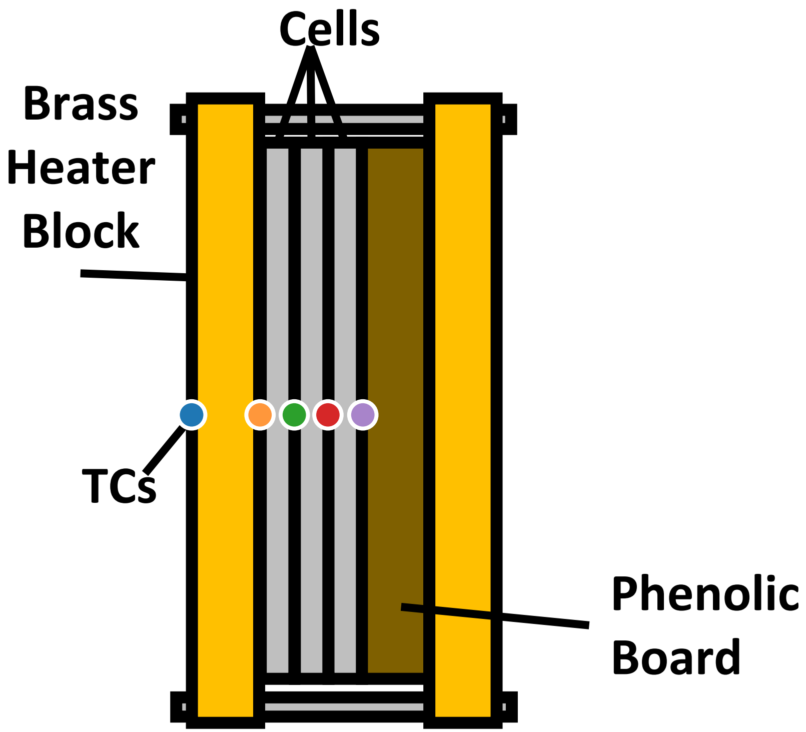
Cell #	Ambient Temp. (˚C)	Discharge Rates	Currents (A)
1,2	15	1C, 4C, 8C, 12C	4, 16, 32, 48
3,4	25	1C, 4C, 8C, 12C	4, 16, 32, 48
5,6	35	1C, 4C, 8C, 12C	4, 16, 32, 48
7,8	45	1C, 4C, 8C, 12C	4, 16, 32, 48

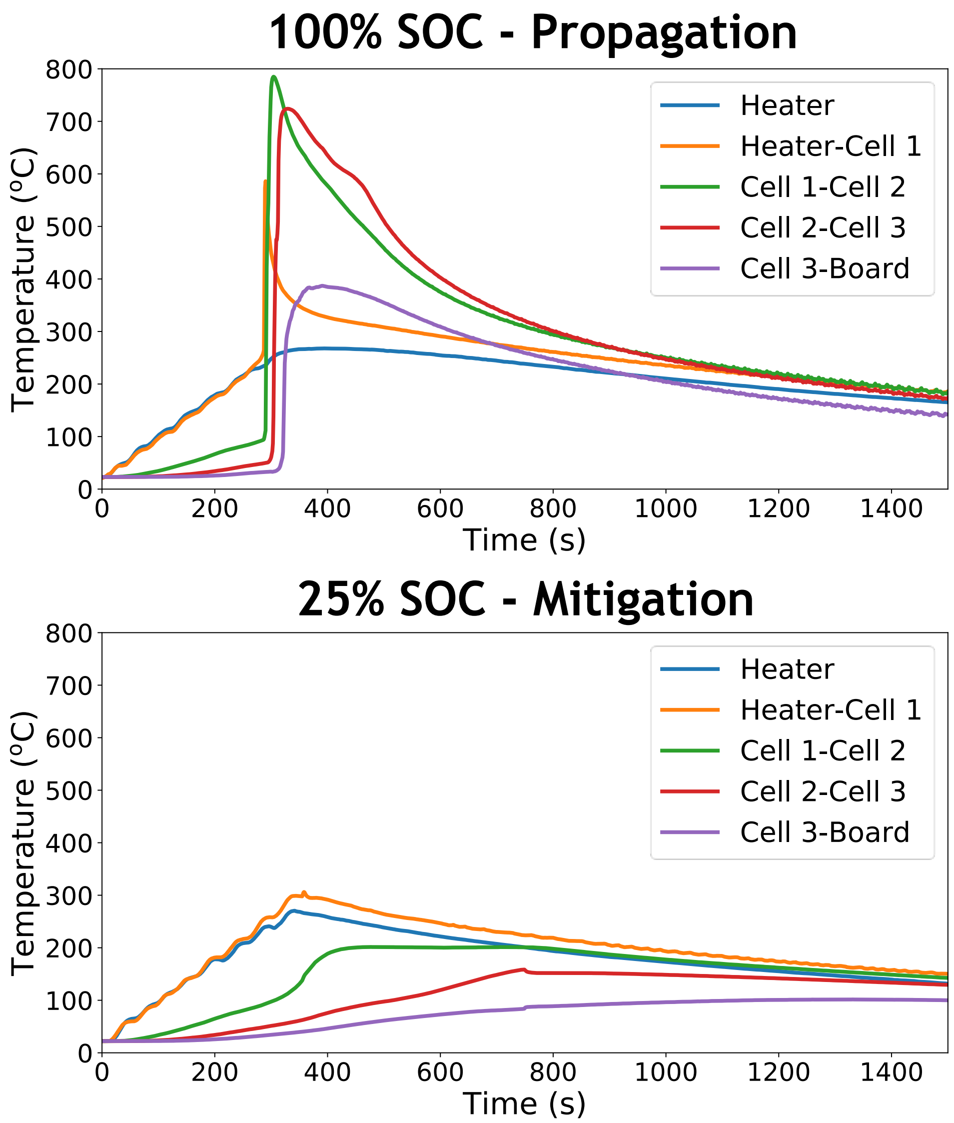




Model Refinements: SOC Propagation/Mitigation Boundary

- **Goal**: Find SOC cutoff and total energy released
- External heating applied to first cell at 50°C/min
- Boundary between 35% and 40% SOC for this heating rate

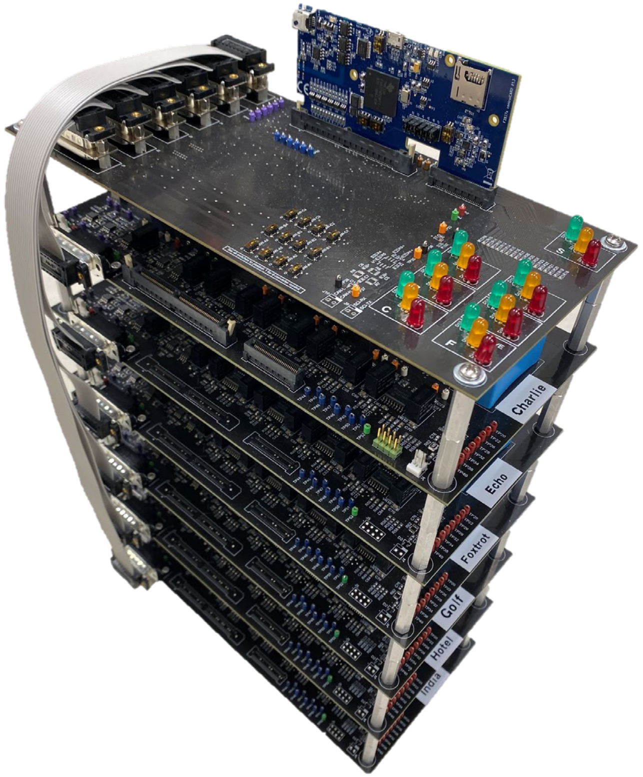




Conclusions

Simulation studies show feasibility of an active electrical response to thermal runaway

- Depleting modules along the pathways taken by thermal energy obstructs module-to-module propagation
- This response mechanism delays, and in some cases fully arrests, propagation of thermal runaway through the system
- Efficacy of response depends on:
  - Rate at which energy can be removed
  - SOC at time of failure
  - Thermal conductivity between modules and ambient environment



Next Steps

- Current models are sufficient for proof of concept, but many refinements are needed:
  - Rapid discharge heating – experiment in progress
  - Module-level thermal runaway
  - More sophisticated thermal network models
- Need to develop ways of predicting module time-to-failure to inform energy dispersion control strategies

Acknowledgements

Thanks For Your Attention

This work was supported by the US DOE Office of Electricity Energy Storage Program under the management of by Dr. Imre Gyuk

For further information, please contact:

Jake Mueller
jmuelle@sandia.gov

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Backup Slides: Multi-Stage Power Conversion

The increasing role of energy storage in grid operation will eventually require more **scalable**, **flexible**, and **fault tolerant** power conversion systems.

There are many candidate topologies, but all share one thing in common: **more granular control over storage resources**.

When we have these systems in place, **how can we use them to improve safety and reliability**?

Modular system architecture, plug-and-play replacement of DC-DC converter modules

Potential for fault-tolerance at the module-level, elimination of (most) single points of failure

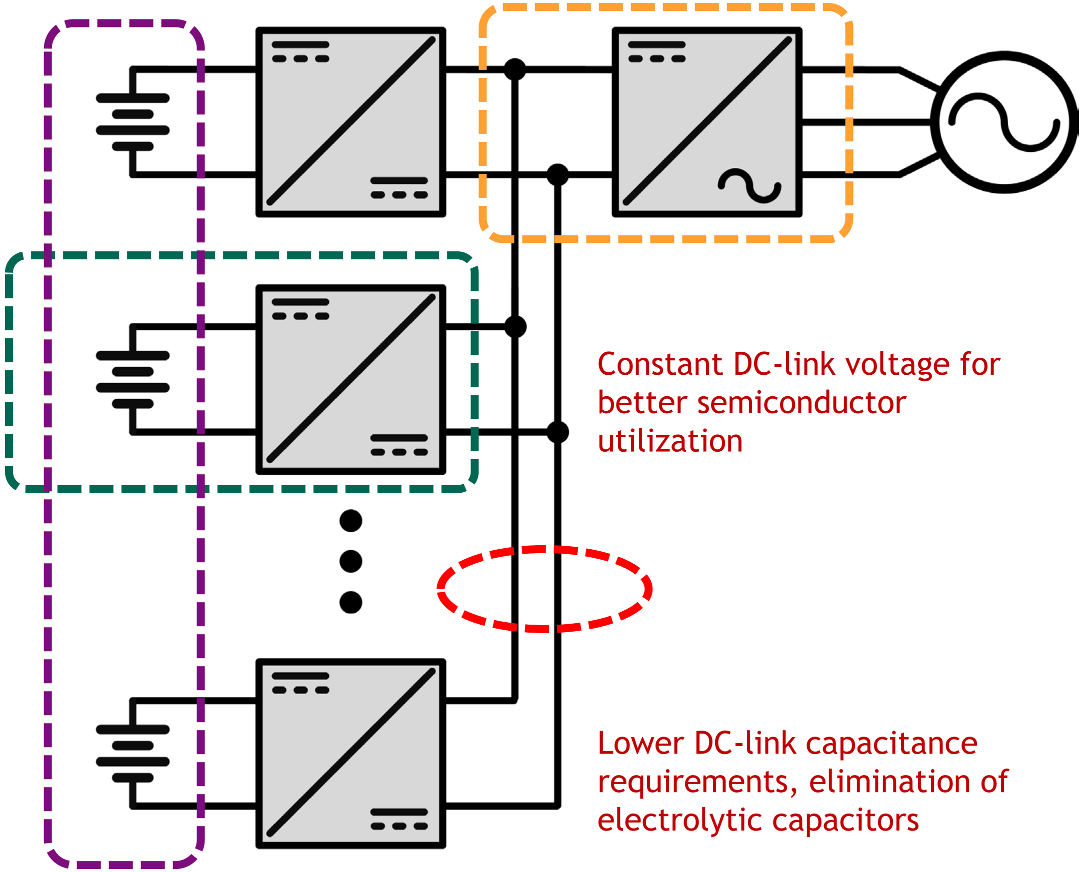
Non-uniform storage systems (e.g. second-life batteries, hybrid storage)

More effective ripple current suppression

Support for long-term evolution of storage device technologies

Multi-level inverters for DC-AC conversion at higher power, higher efficiency, better power quality

Elimination of line frequency transformers



Constant DC-link voltage for better semiconductor utilization

Lower DC-link capacitance requirements, elimination of electrolytic capacitors