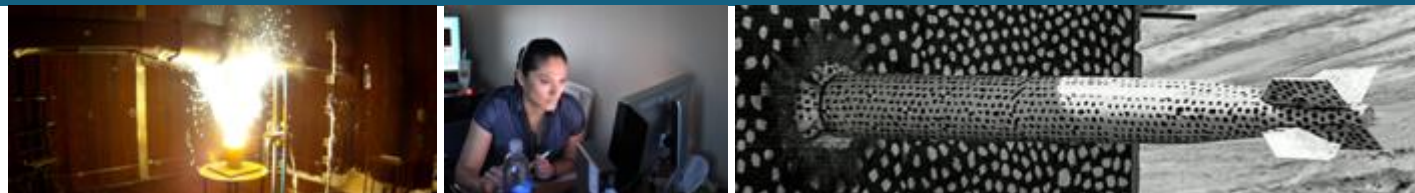


Energy Redistribution in Response to Thermal Runaway



PRESENTED BY

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The Good

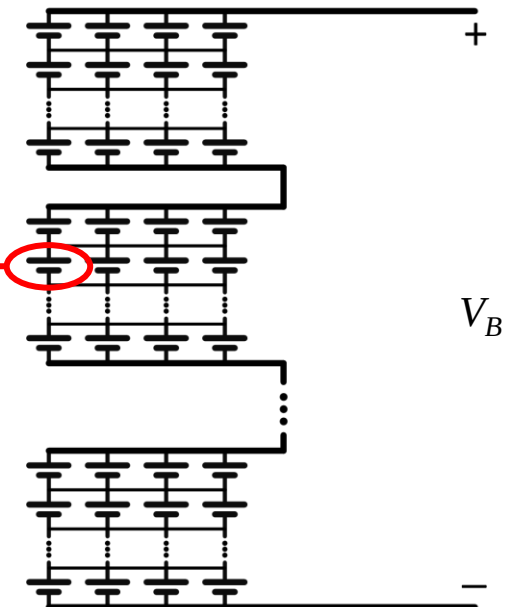
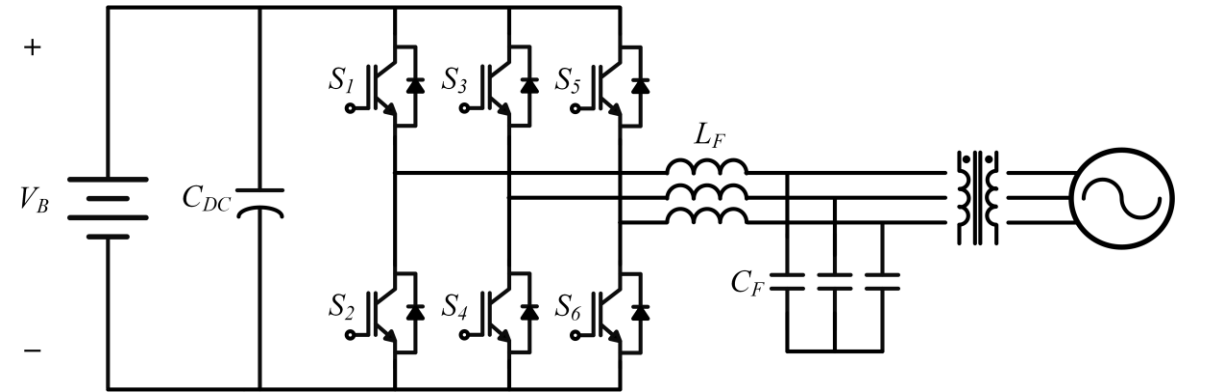
- + Simplicity: Simplest possible converter topology
- + Price: Lowest capital cost

The Bad

- Scalability: Storage system must be designed around min and max DC link voltage constraints
- Flexibility: All storage devices must be identically matched or performance degrades
- Storage Utilization: Effective power/energy of series-connected cell strings is limited by the weakest cell
- Wasted Silicon: DC link voltage variation with SOC and system age leads inexorably to poor converter utilization
- Reliability: Every cell in a series-connected string is a single point of failure

The Very Bad

- X The severity of these deficiencies increases as DC-link voltage increases
- X To achieve higher power, need higher working voltage
- X So the cost of a small increase in power capacity is a massive hit to efficiency, reliability, storage device utilization, and more



If this cell needs to be replaced, what happens to the rest?

Multi-Stage Power Conversion Structures



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

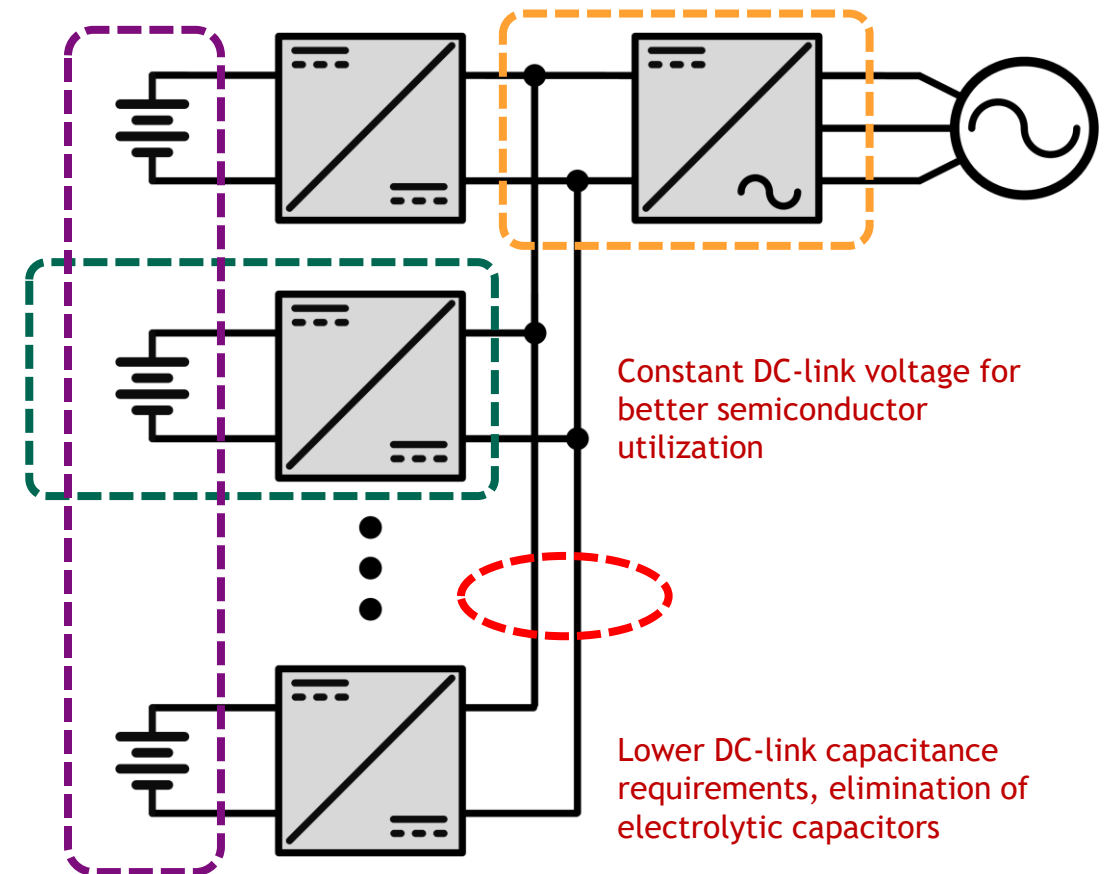
Non-uniform storage systems (e.g. second-life batteries, hybrid storage)

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



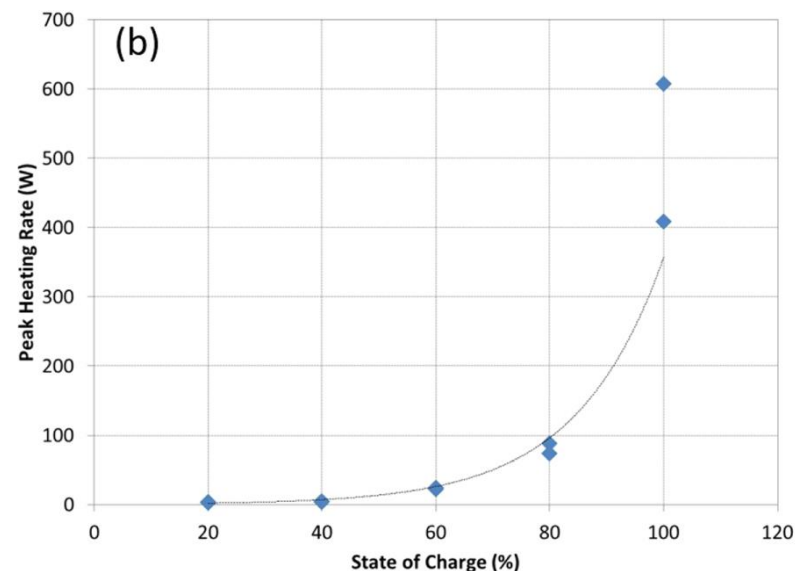
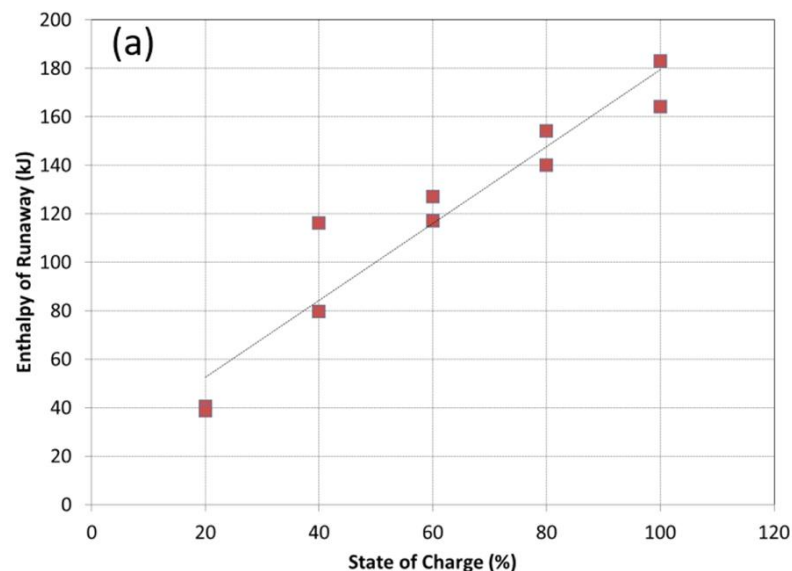
Factors Influencing Thermal Runaway



What determines the severity of a thermal runaway event?

- Total energy released
- Rate at which energy is released
- Module-to-module thermal conductance versus heat dissipation

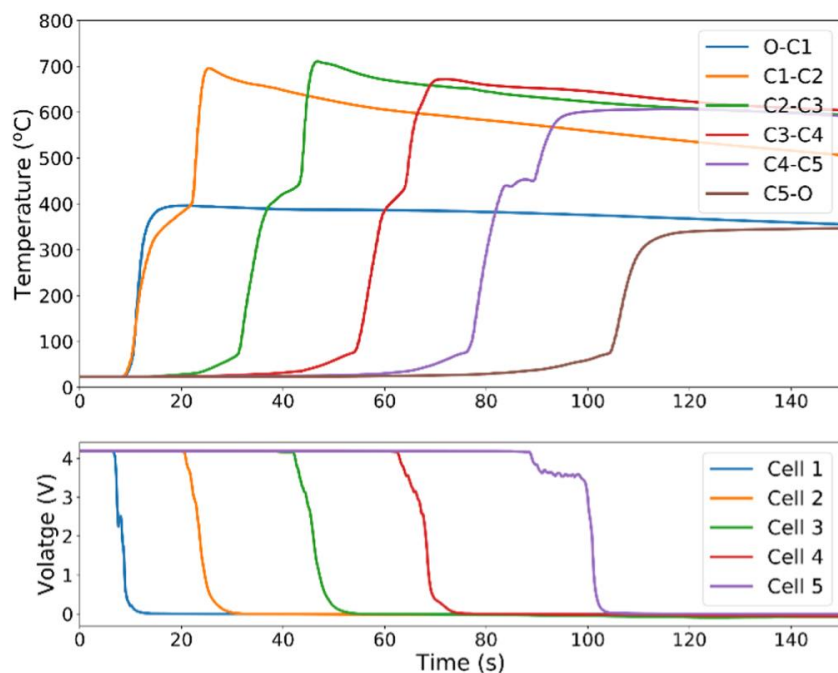
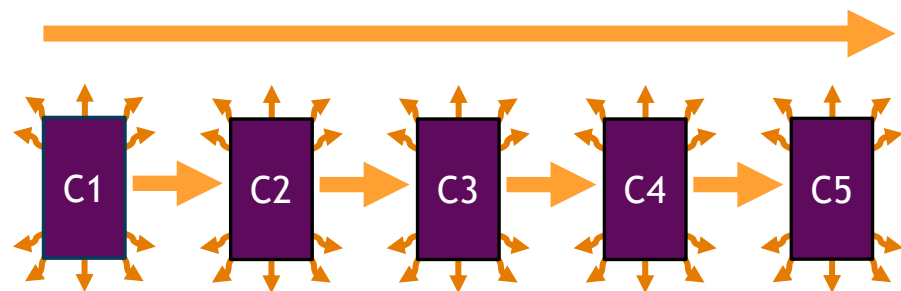
First two depend on state of charge, last on system design.



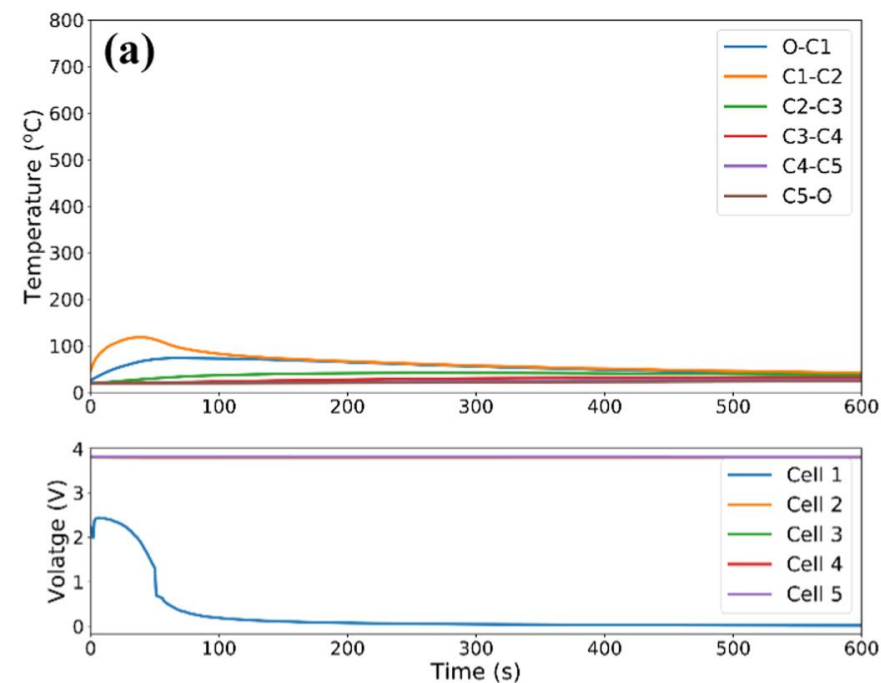
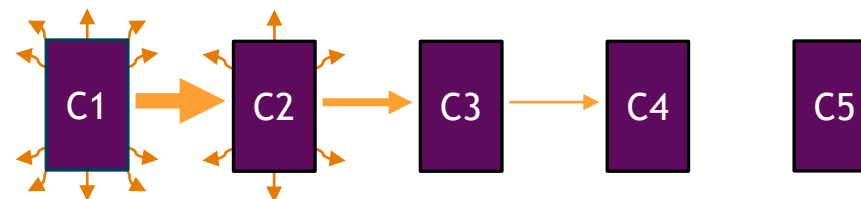
Propagation and Mitigation of a Thermal Runaway Event



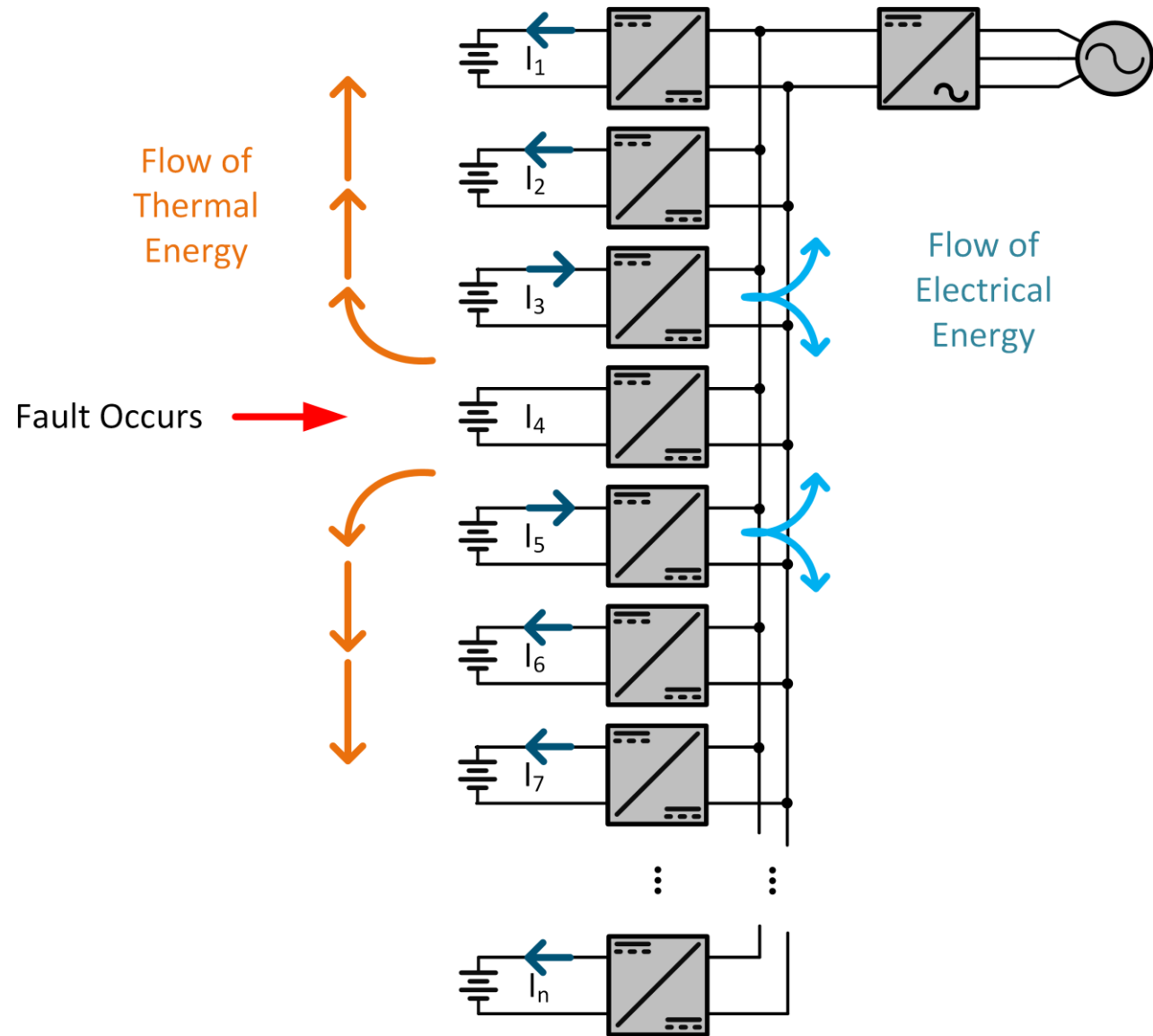
Propagation for cells at 100% SOC

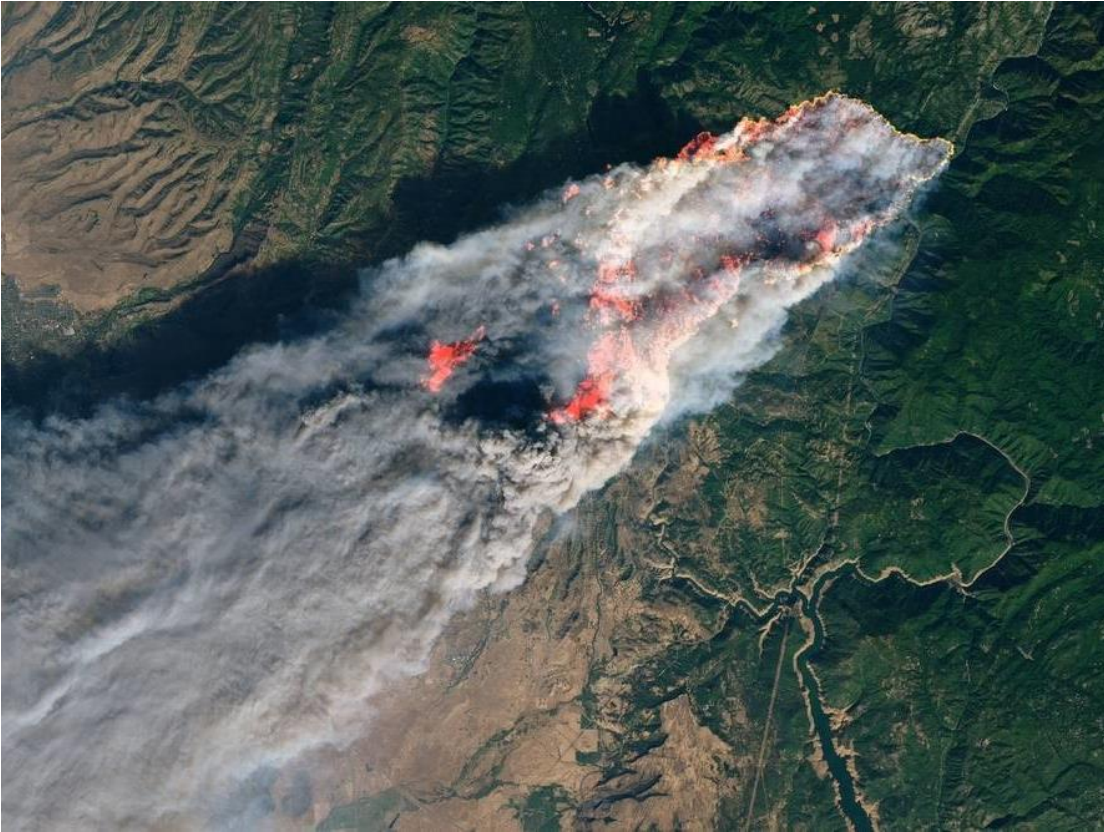


Mitigation for cells at 50% SOC



6 Energy Redistribution





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?

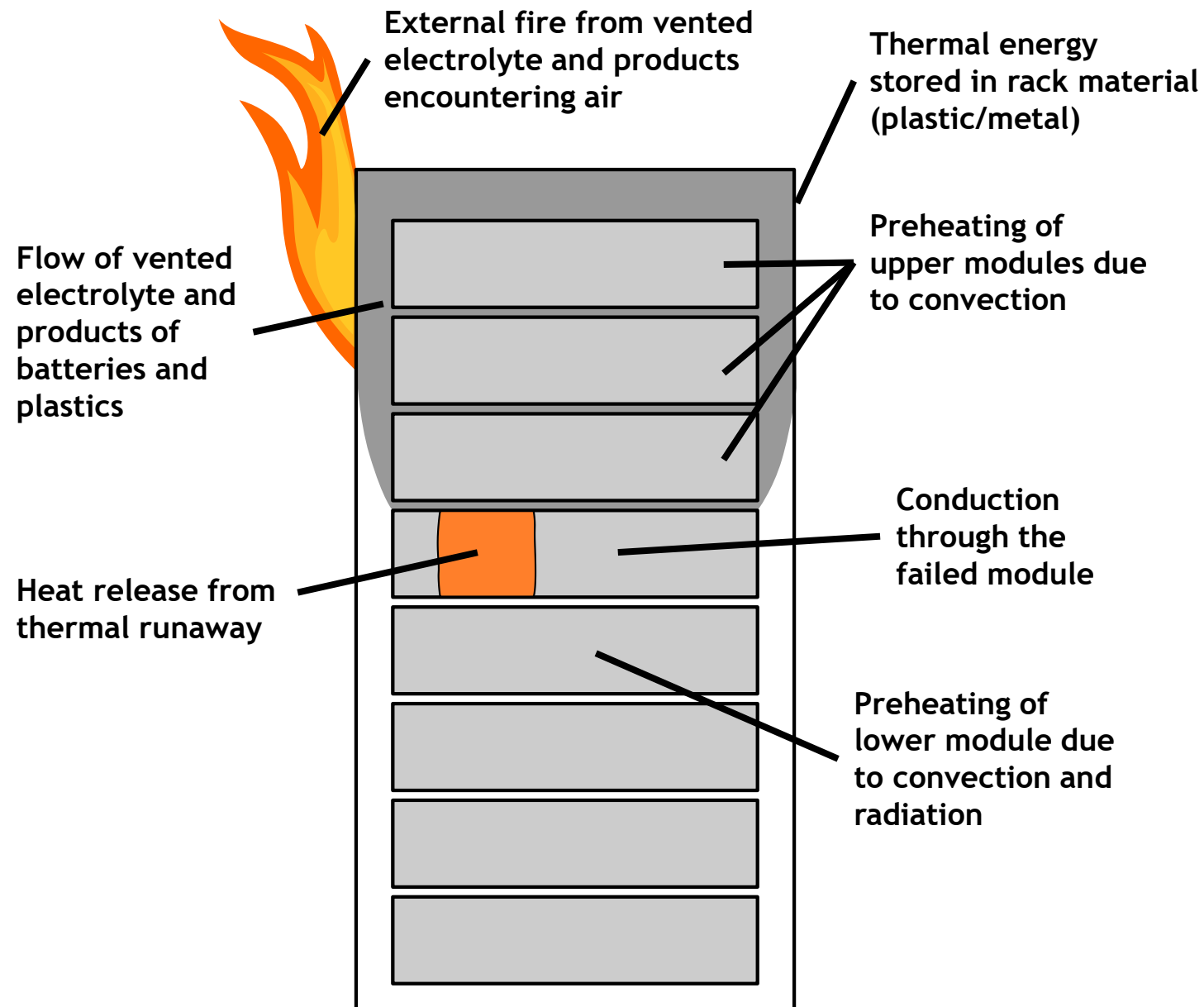
How wide does it need to be?

How much time do you have to respond?



Question 1: Where to intervene?

- Which module(s) should be discharged to most effectively obstruct propagation of thermal runaway?
- Answer depends on location of initial failure event and pathways taken by thermal energy released from the failure
- Determination of thermal energy pathway is very complex, depends strongly on mechanical system structure

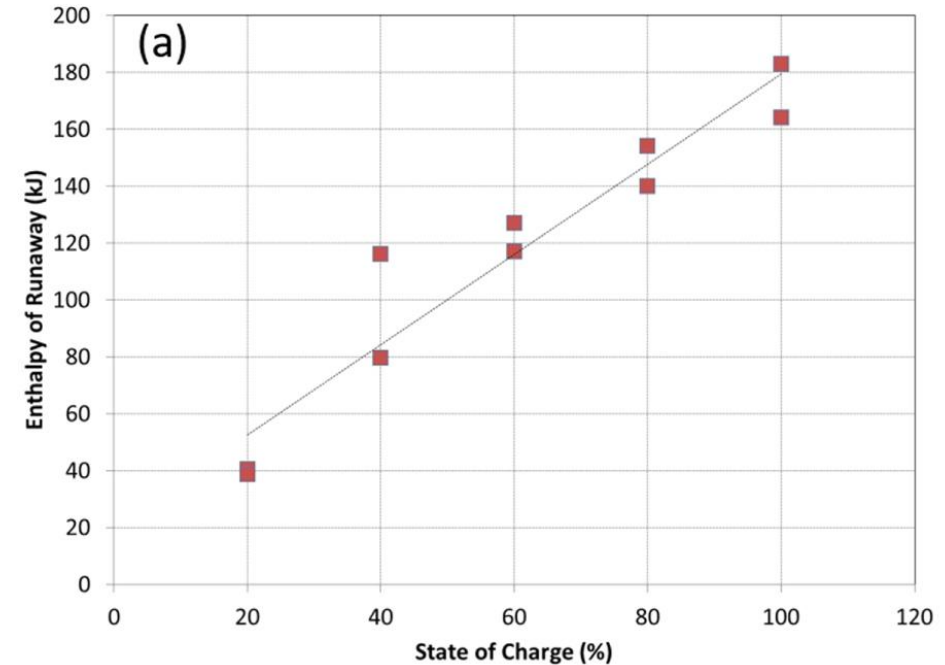


Question 2: How deeply to discharge?

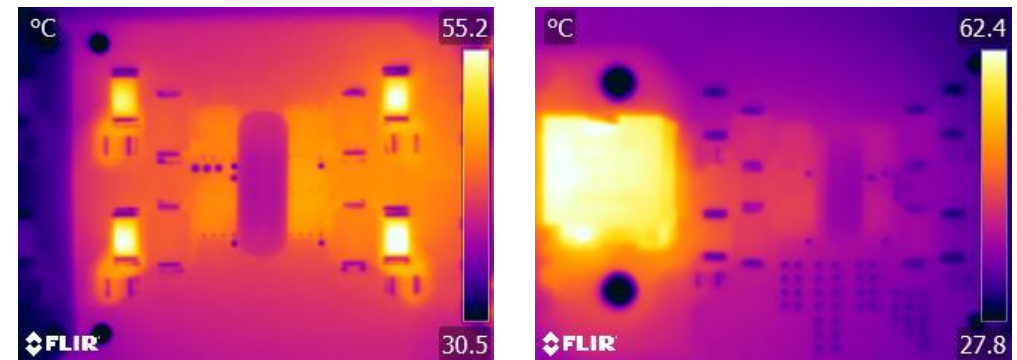
- Cell-to-cell propagation cannot continue at low SOC. Does this generalize to module-to-module propagation?
- Is there value in deeper discharge?

Question 3: How much time to respond?

- How long does module-to-module propagation take with no intervention?
- How does preheating due to rapid discharge affect propagation times?
- How long before the converter fails?
- How hard do you drive the converter?



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



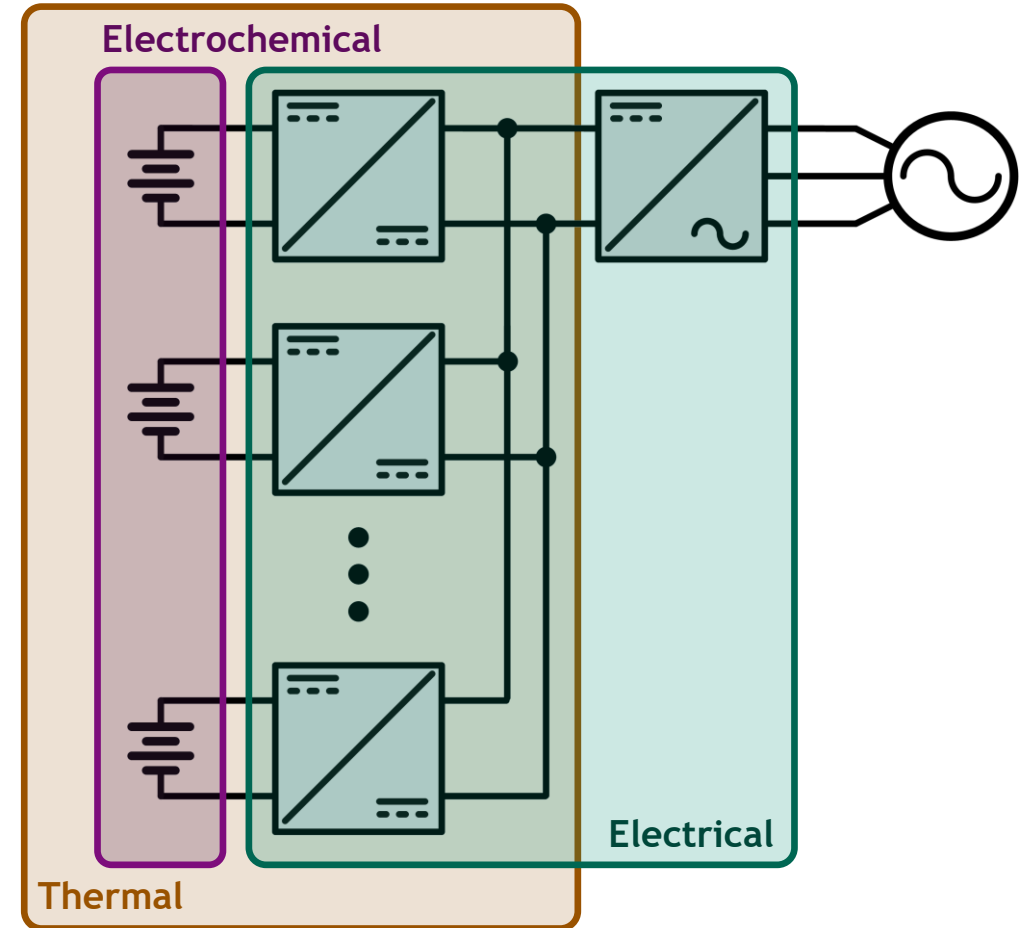
Component temperatures in DAB converter at low side (left) and high side (right) H-bridges when operating at 50% above max rated power

System Under Consideration

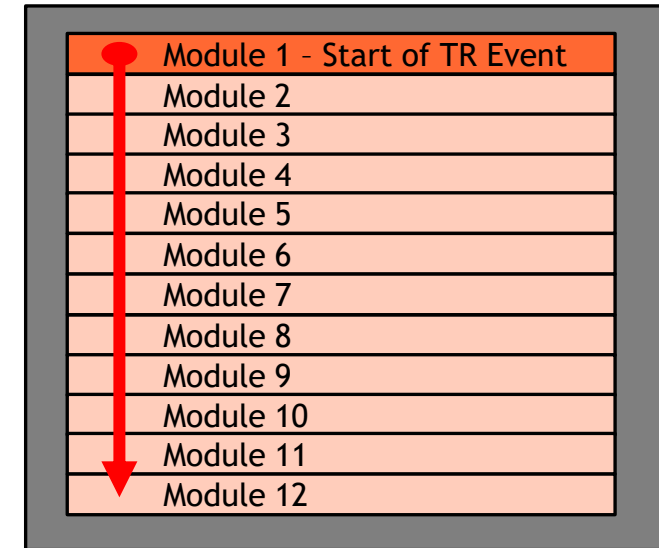
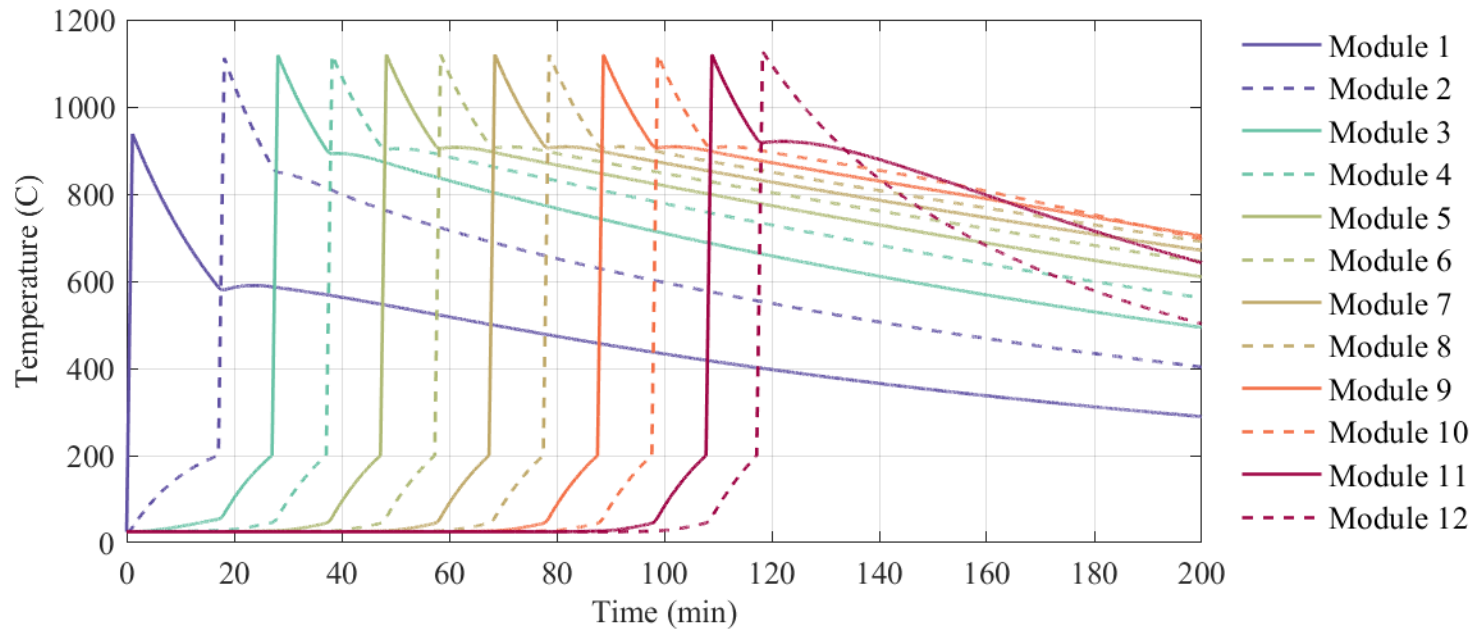
- 160kW/80kWh system organized into 12x rack-mount modules
- Each module consists of storage devices and a DC-DC converter, modules connect in parallel to common DC bus
- Storage modules
 - Rated power/energy 13.2kW/6.6kWh
 - Module capacity 128Ah, nominal voltage 52V
 - Capable of 2C continuous discharge
- DC-DC converters
 - Modeled as bidirectional buck converters for simplicity
 - Power/voltage ratings matched to storage modules
 - Converters fail when temperatures exceed 100° 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



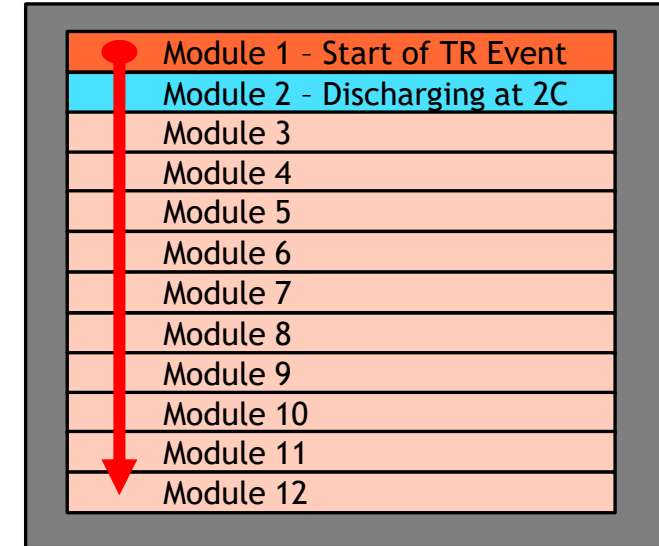
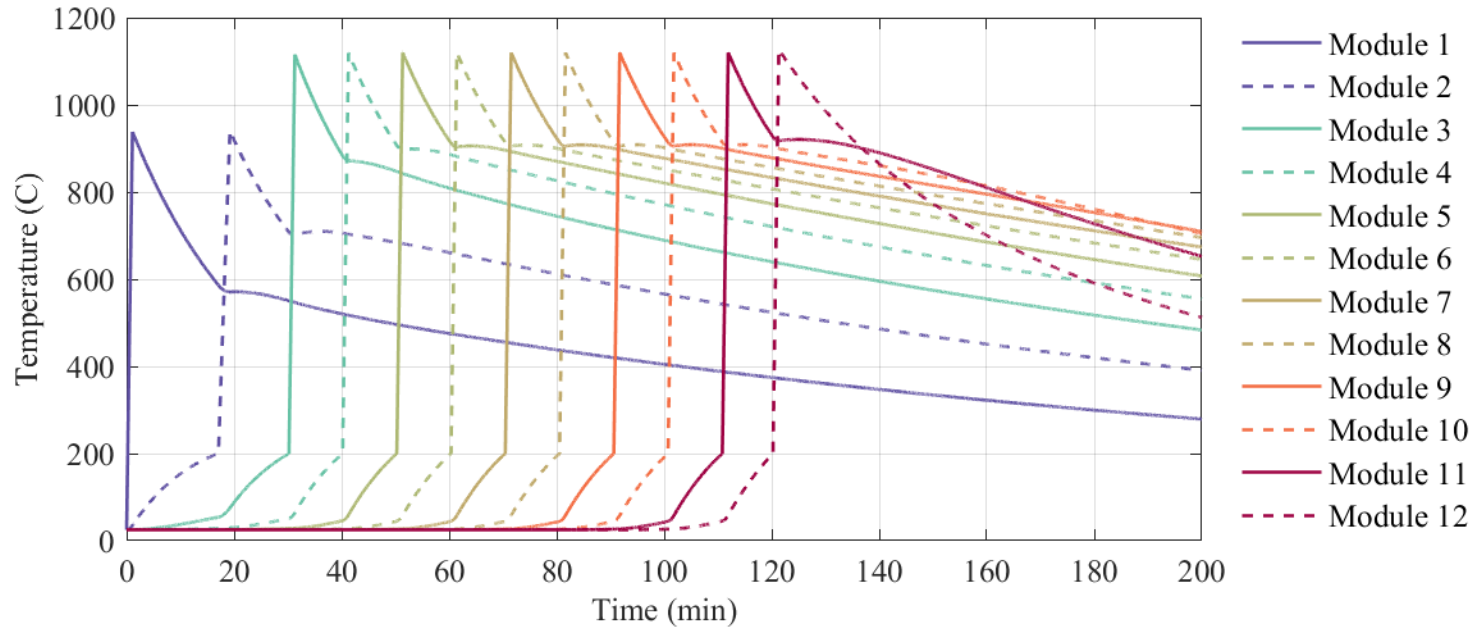
Case I – Propagation with No Intervention



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

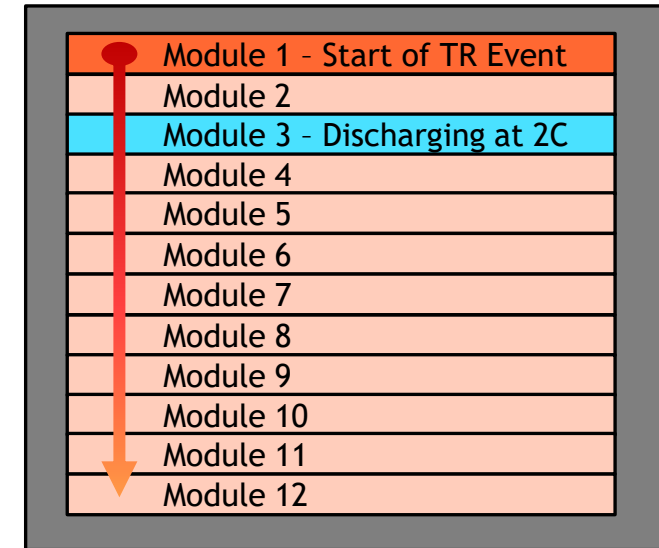
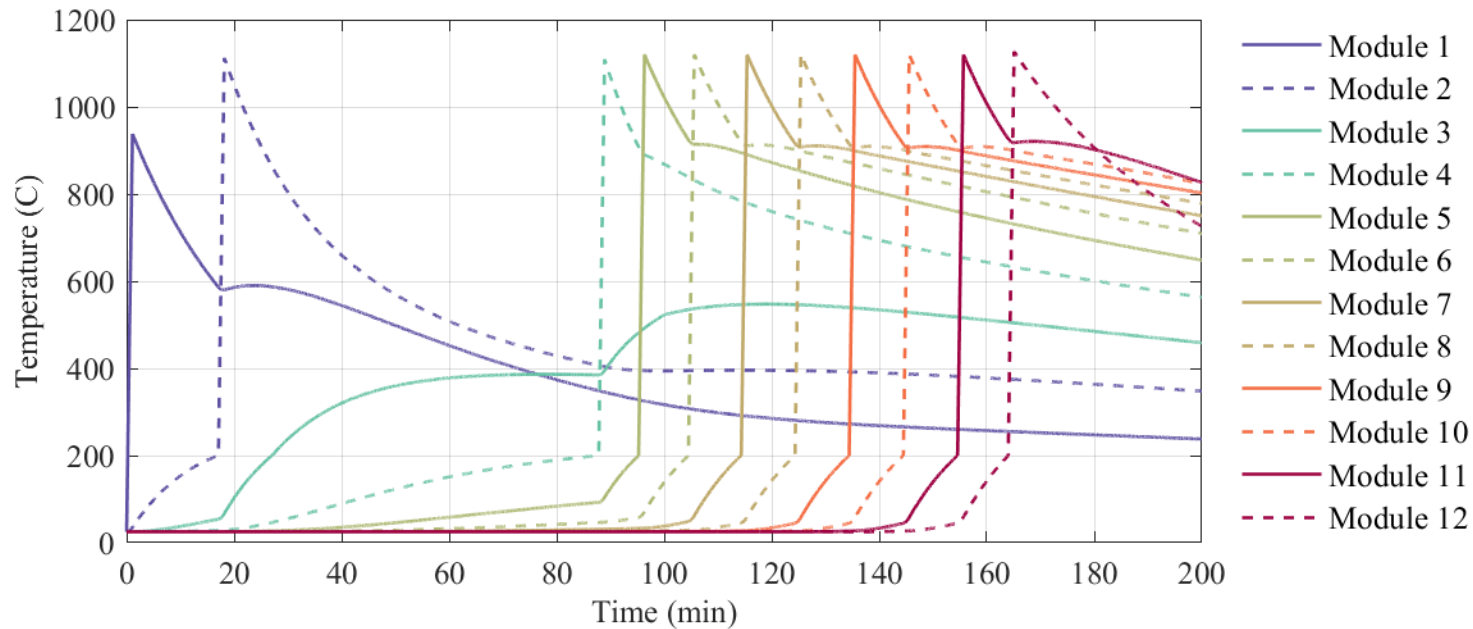
Case 2 – Intervention at Adjacent Module



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

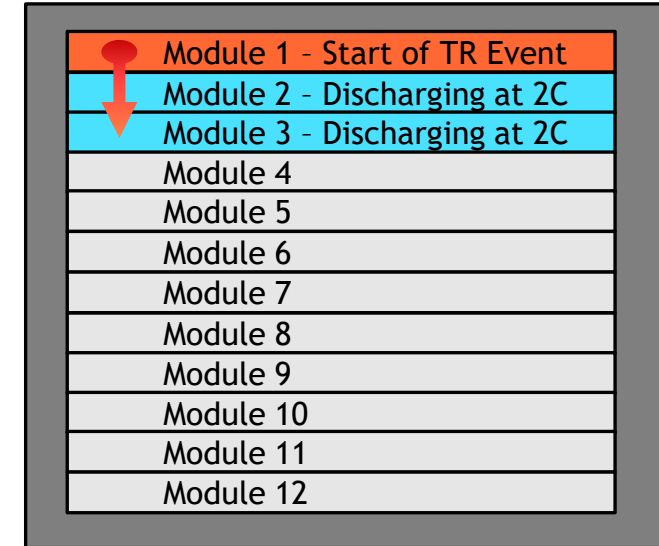
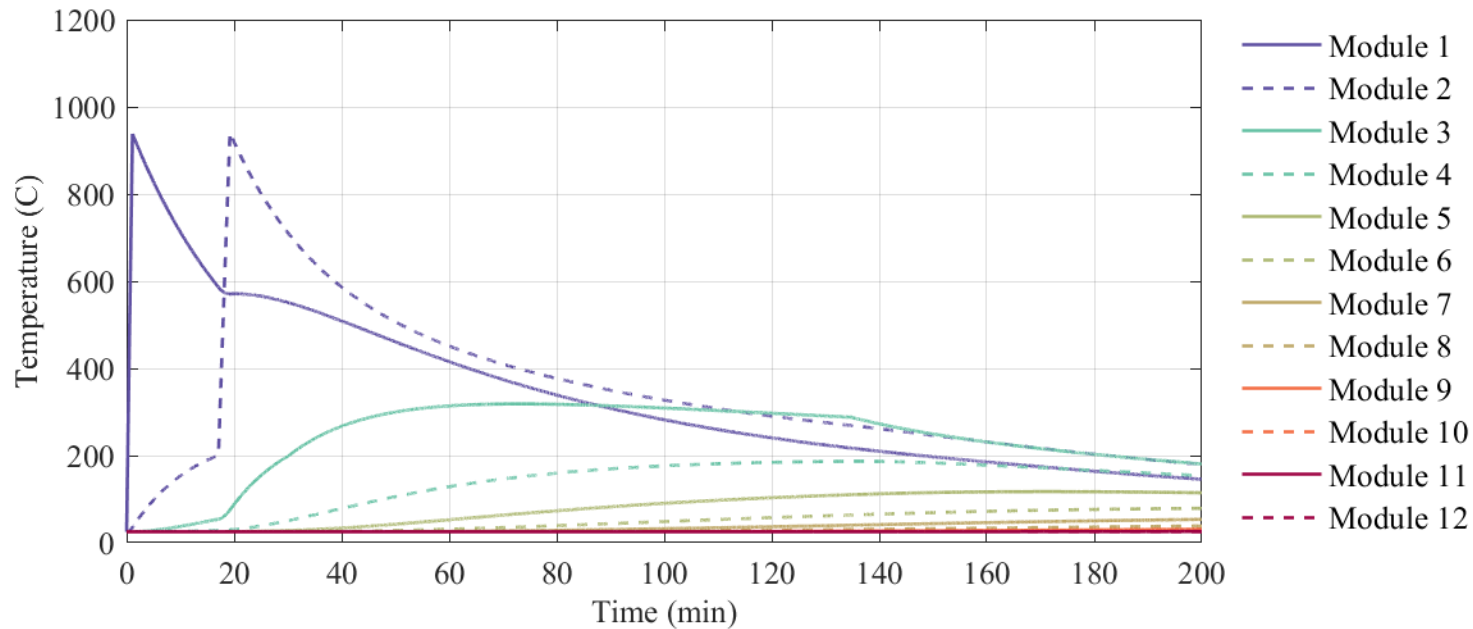
Case 3 – Intervention at Second Adjacent Module



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



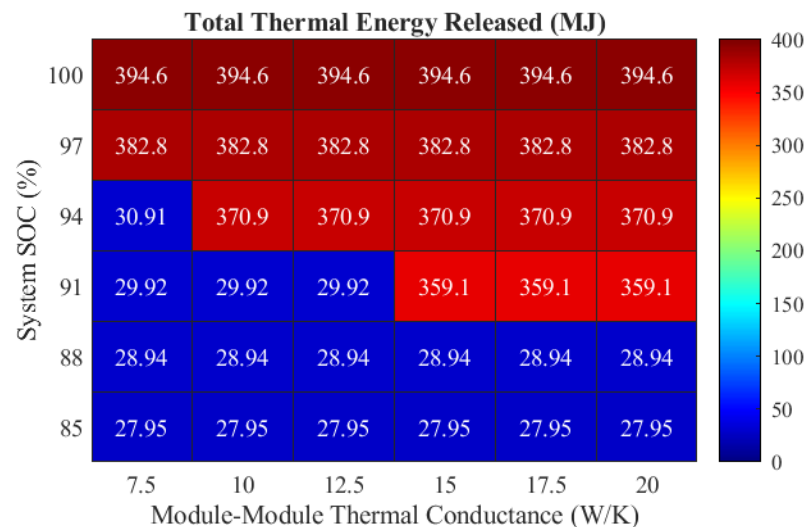
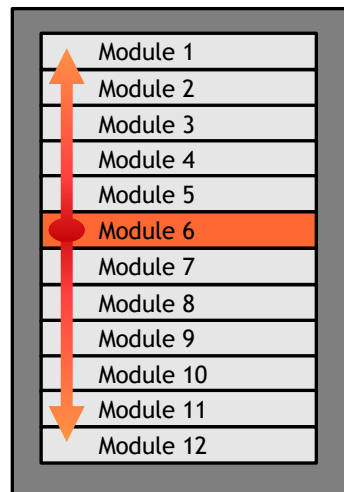
Success – Propagation is Arrested

- 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

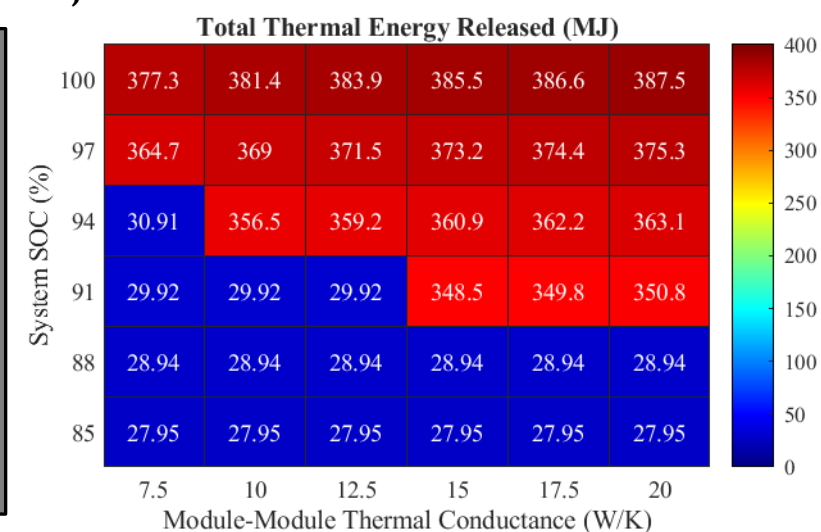
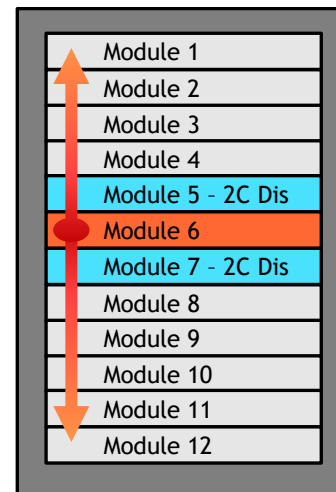
Energy Release vs SOC, Thermal Conductance, and Response Type



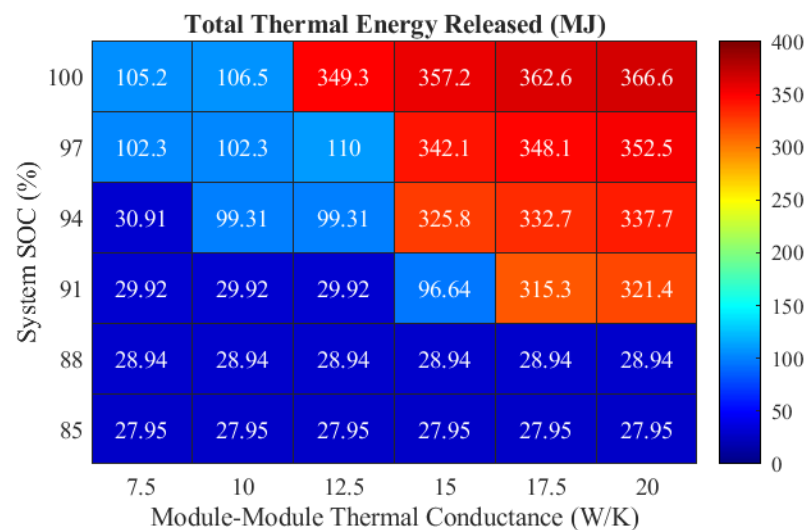
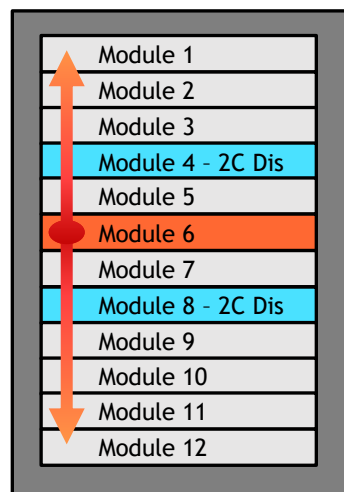
No Intervention



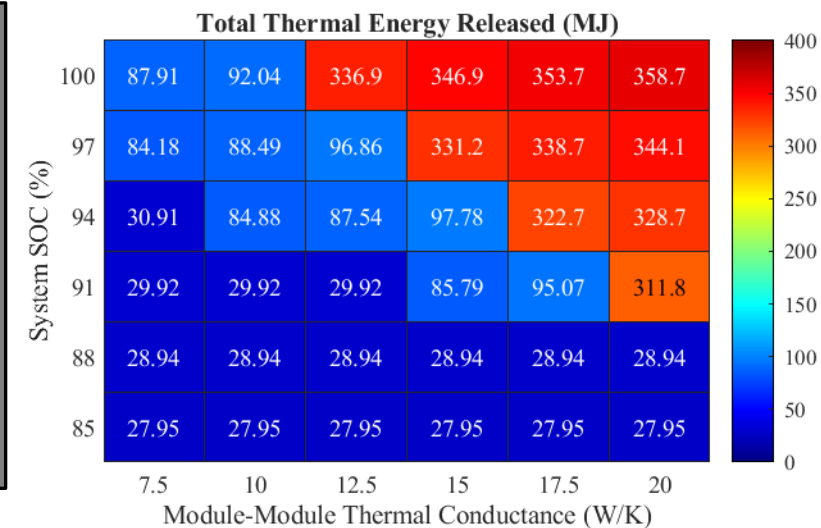
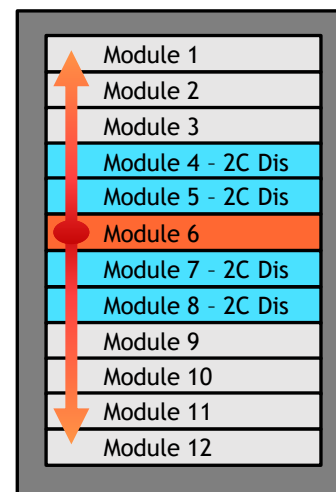
Intervention in 1st Adjacent Module



Intervention in 2nd Adjacent Module



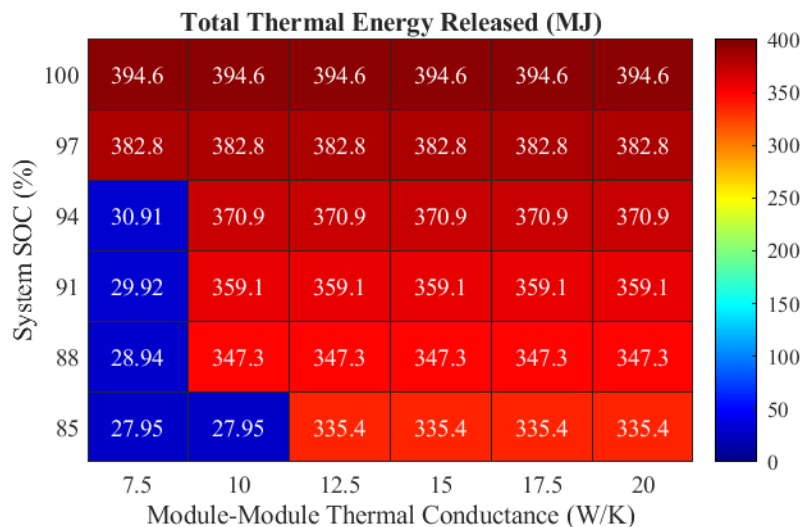
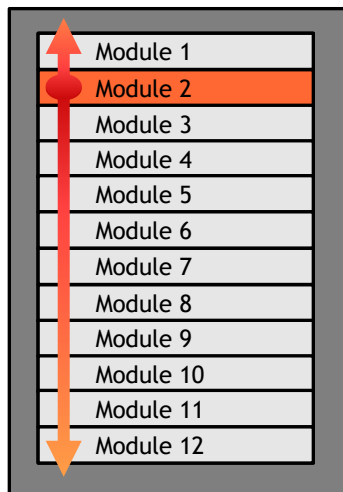
Intervention in 1st and 2nd Adjacent Modules



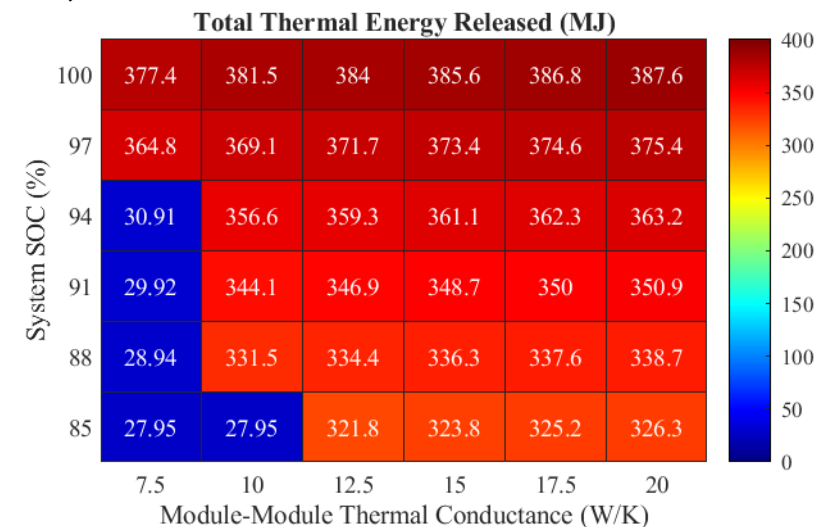
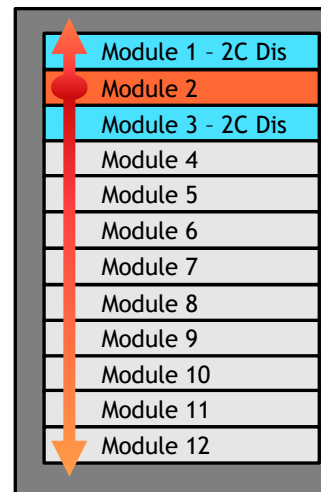
Energy Release vs SOC, Thermal Conductance, and Response Type



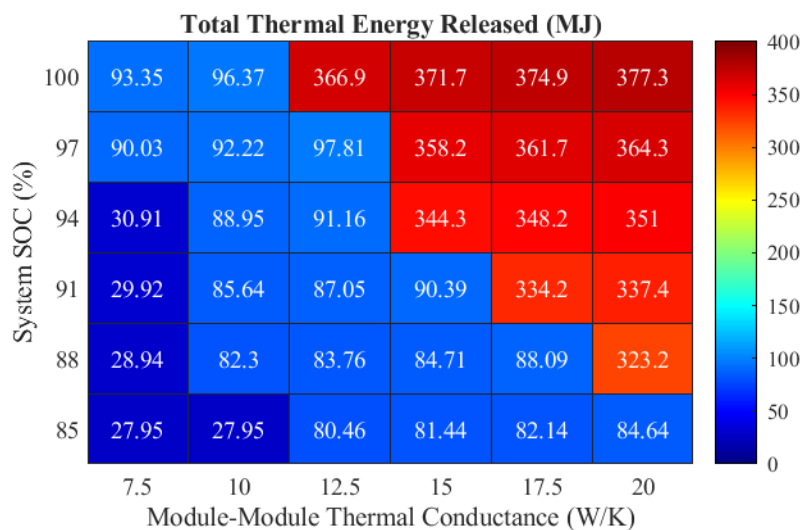
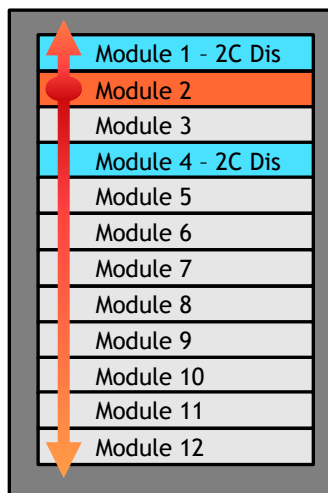
No Intervention



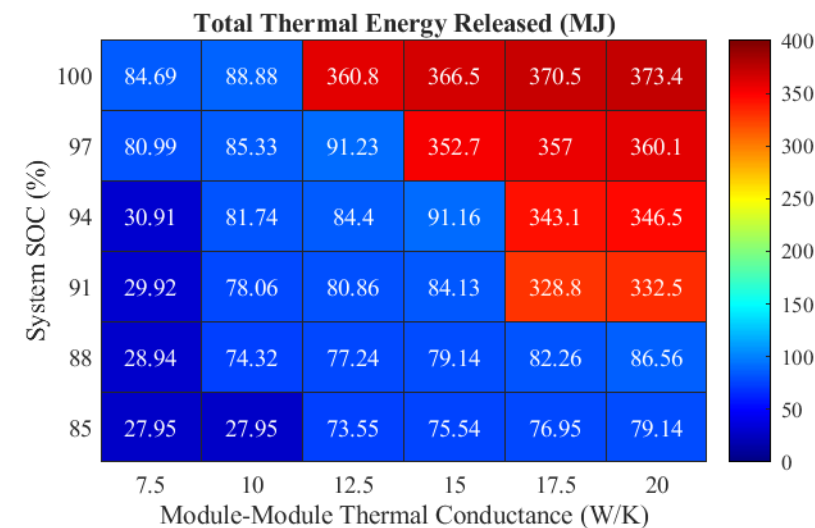
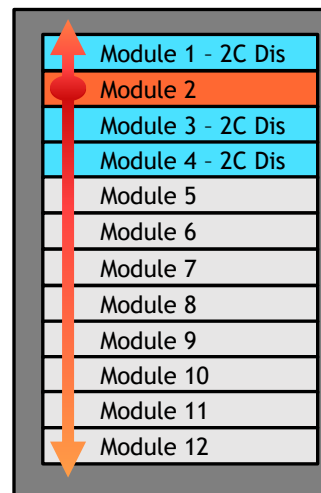
Intervention in 1st Adjacent Module



Intervention in 2nd Adjacent Module



Intervention in 1st and 2nd Adjacent Modules





New power conversion architectures provide new options for addressing existing problems

- The principal benefit of advanced power conversion architectures is **finer control over the energy within the system**
- We will need new power conversion architectures for other reasons, so we might as well use them to improve safety and reliability
- The ability to exert more control over energy resources is a good match for safety and reliability challenges, which essentially involve unintentional/uncontrolled release of energy

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

Important questions remain

- Does it really work? No substitute for hardware results
- How does the behavior of propagating thermal runaway scale up from cell to module?
- Our thermal network model is oversimplified—what generalizable features exist in the thermal structure of real storage systems?



Thanks For Your Attention

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Office of Electricity Energy Storage Program

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