

# ENERGY STORAGE SYSTEMS

SAFETY & RELIABILITY FORUM

# What Causes **Thermal Runaway** and What Are the Materials Processes Involved?

A foundational exploration of battery failure science, covering microscopic mechanisms, triggers, and safety implications for energy storage systems.

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JUNE 2, 2026

# AGENDA

- Introduction to Thermal Runaway
- Battery Components and Materials
- Thermal Runaway Mechanism
- Initiation Methods
- Critical evaluation of “Safe” Chemistries
- Scaling Up Safety
- Closing Remarks



# Learning Objectives

**By the end of this tutorial, we will be able to:**

- 1) *Define what thermal runaway is and what its hazards are.*
- 2) *Identify which reactions contribute to thermal runaway.*
- 3) *Identify thermal runaway initiation methods.*
- 4) *Determine differences in hazards dependent on battery chemistry.*
- 5) *Critically assess claims of safety for new chemistries.*
- 6) *Determine thermal runaway hazards associated with system scale-up.*



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# Battery Storage Is Growing Fast — And the Safety Science Needs to Keep Up

*Modern grid-scale ESS installations: Scaling brings new safety challenges.*



## Global Scaling

Grid-scale and distributed ESS are expanding rapidly worldwide.



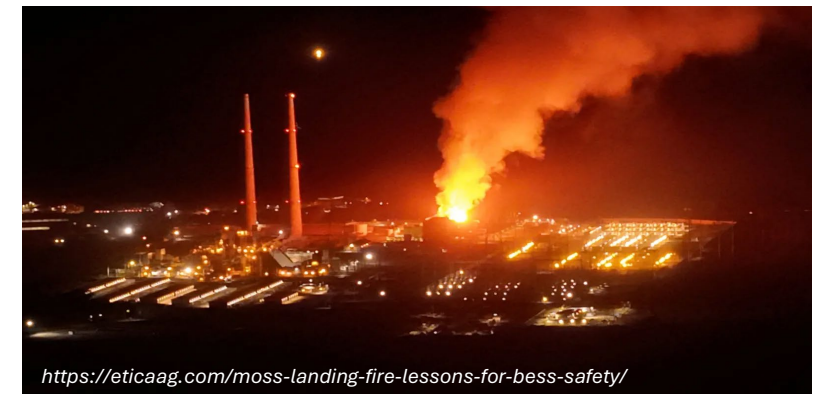
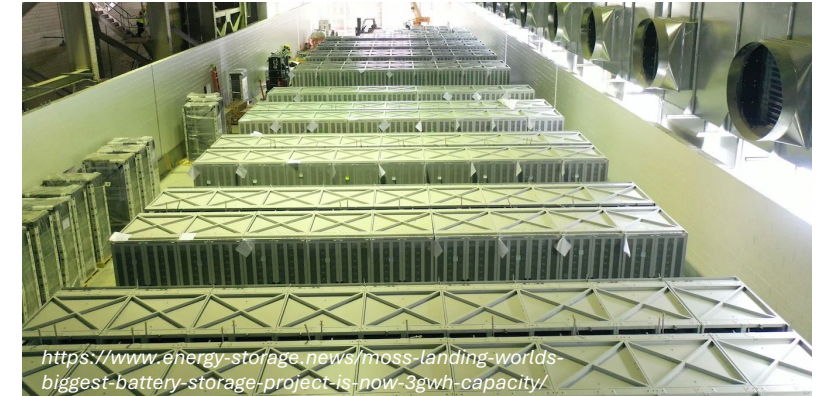
## Amplify Consequences

Larger deployments mean single-cell failures can have system-wide impacts.



## Foundational Safety

Understanding cell-level science is not optional—it is the foundational requirement for every informed safety decision



# Energy Storage Systems Face Several Hazard Types — Thermal Runaway Drives the Most Severe Outcomes



## Electrical

Arc flash, short circuits, high-voltage DC risks.



## Mechanical

Internal pressure, structural failure, vibrations.



## Chemical

Electrolyte leaks, coolant exposure, toxicity.



## Thermal

Thermal runaway: self-propagating.

### Why is Thermal Runaway distinctive?



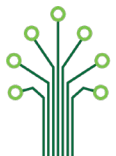
**Self-Amplifying:** Batteries contain both oxidant and reductant, making it uniquely difficult to interrupt.



**Escalating Consequences:** Can spread to neighboring cells (propagation), scaling with deployment size.



**Diverse Hazards:** Can produce fire, toxic gas, and overpressure simultaneously.



# Thermal Runaway Is a **Self-Accelerating Process** — Fire Is One Possible Outcome, Not the Definition



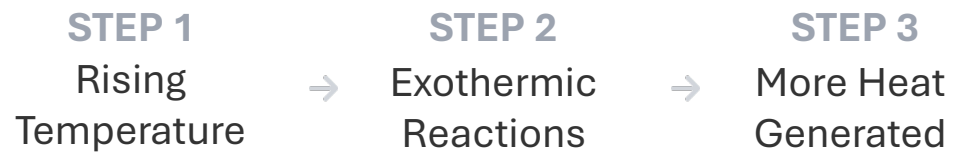
## The Heat Balance Failure

A condition where a cell generates heat **faster than it can release it** to its surroundings - Accumulation.






**Generation > Dissipation**



## Self-Reinforcing Cycle



## Possible Outcomes

-  Venting & Gas Release
-  Swelling & Deformation
-  Fire & Combustion
-  Overpressure & Explosion
-  Toxic Vapor Cloud

*\*Outcomes depend on cell chemistry, state of charge, and environmental conditions.*



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# Cell Architecture: What We Are Working With

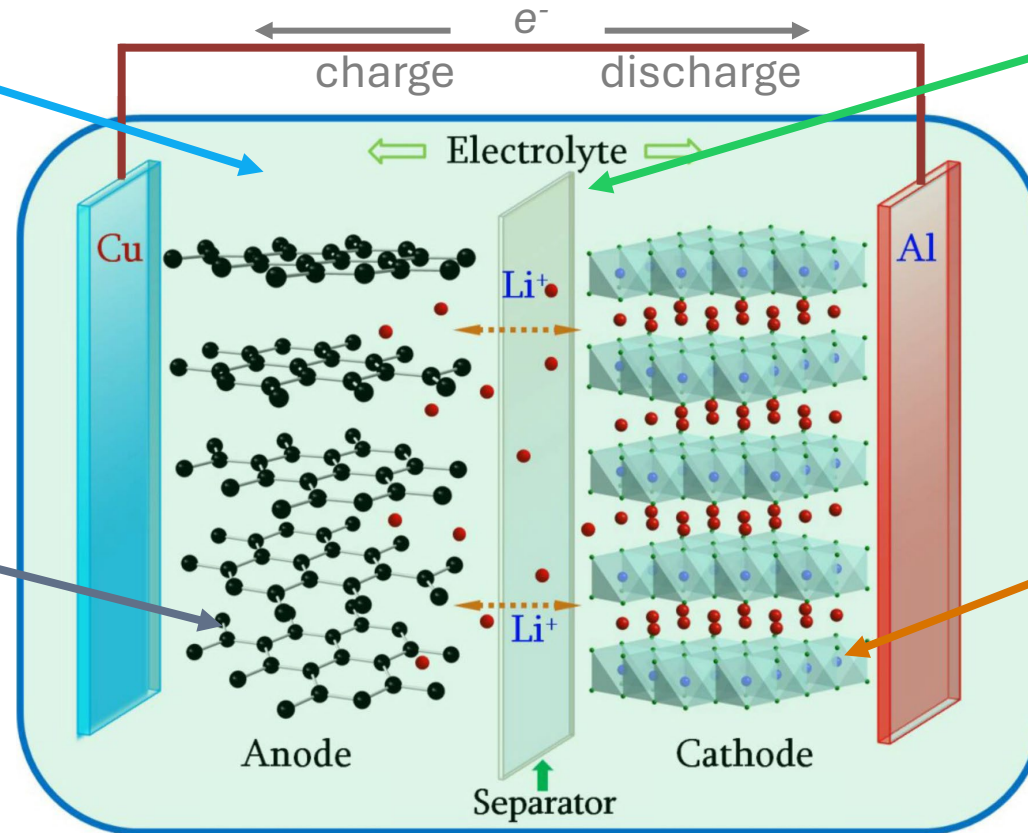
Control depends on maintaining the separation of reactive materials.

## Electrolyte

- Organic liquid solvent (carbon-based)
- Facilitates ion flow between electrodes
- Flammable under runaway conditions

## - Anode (Negative)

- Typically composed of graphite layers
- Hosts lithium ions in charged state
- High reactivity when SEI layer fails



## Separator

- Porous plastic/ceramic membrane (~20 $\mu$ m)
- Prevents physical contact (shorts circuit)
- Melts/shrinks at 120–150°C

## + Cathode (Positive)

- Metal oxide or phosphate structures
- Hosts lithium ions in discharged state
- Can release oxygen at high heat



Energy storage is fundamentally the separation of highly reactive materials.



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# The SEI: The Cell's Built-In But **Fragile First Layer of Protection**

## Selective Membrane

Formed naturally on the anode; permits lithium ions while blocking electrolyte decomposition.

## Thermal Sensitivity

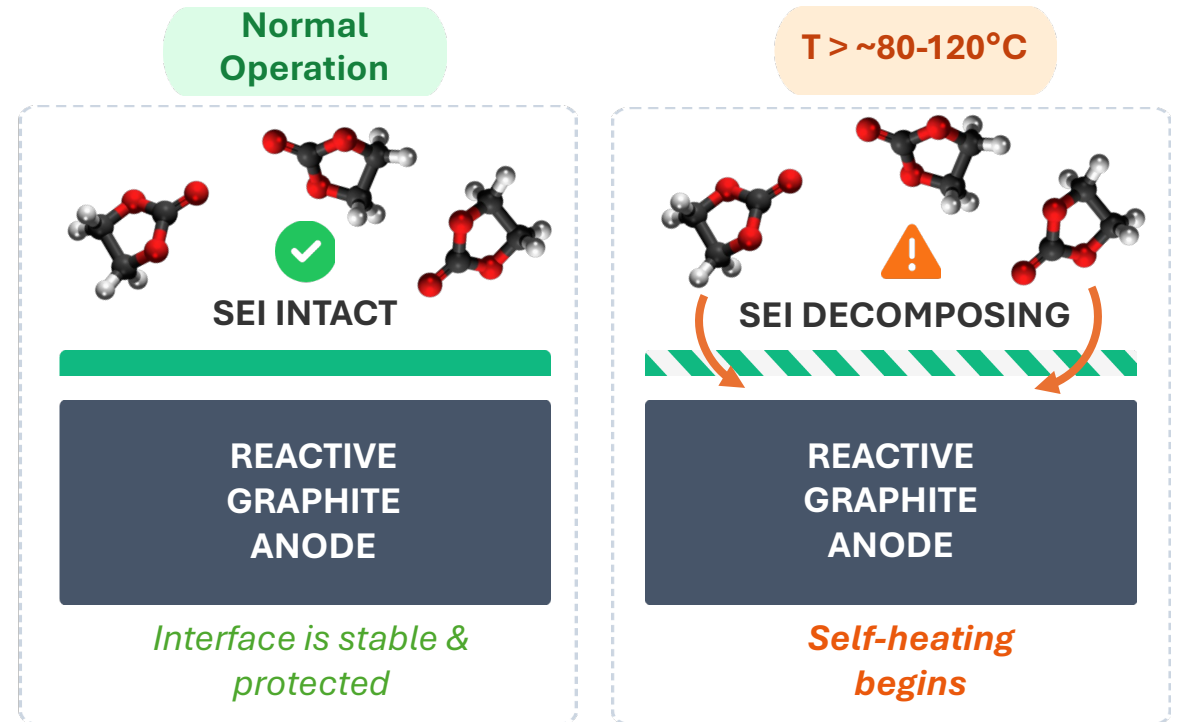
Metastable layer; decomposition typically begins between **~80°C and 120°C**.

## Exothermic Breakdown

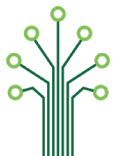
The process releases heat and exposes the reactive anode surface to the electrolyte.

## Stage 1 of the Cascade

Often the triggering chemical event for cells with graphite anodes.



*Note: Thresholds are approximate and design-dependent*



# When the Separator Fails, the Electrodes Make Contact — Releasing Stored Energy Rapidly

## Material Breakdown

- > Polymer films (PE/PP) have defined **melting points**.
- > Heat causes the separator to **shrink, melt, or fail**.
- > Loss of physical barrier allows **direct electrode contact**.
- > Stored electrical energy converts to **intense localized heat**.



### Stage: Intact Separator

Normal operation. Electrodes are physically isolated.



### Threshold: Thermal Instability

*Approximate and design-dependent temperature reach.*







### Event: Internal Short Circuit

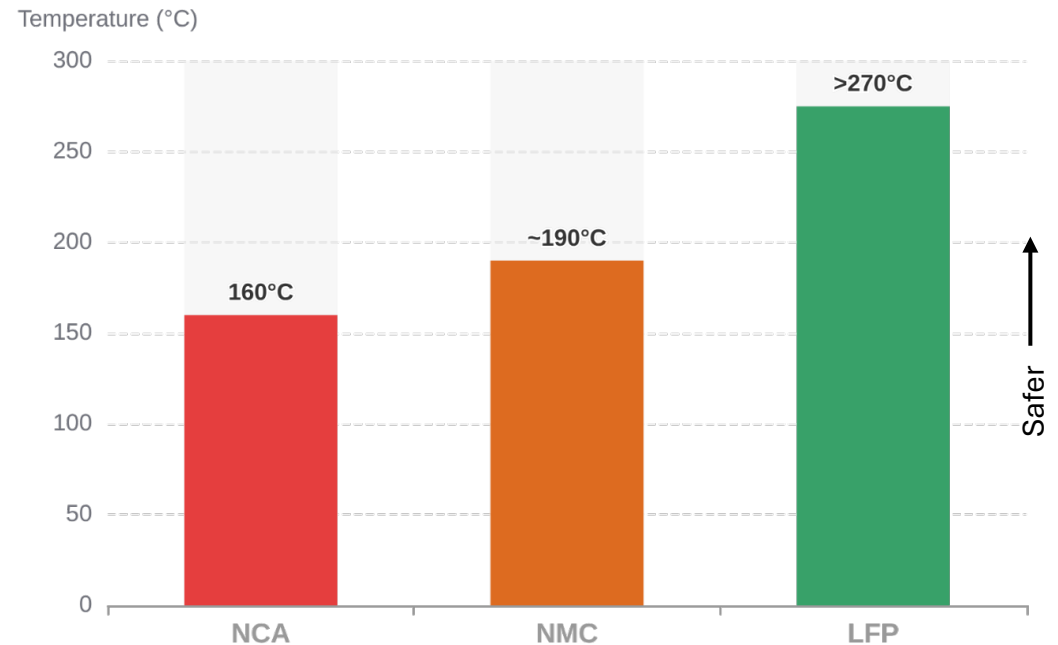
Rapid electrical discharge. Cascade acceleration.



# At High Temperatures, Some Cathode Materials Release Oxygen — Which Can React With the Hot Electrolyte

-  Cathodes are lithium metal oxides; **oxygen** is part of their crystal structure.
-  Heat causes structural instability, releasing lattice oxygen as a **gas**.
-  Released oxygen drives **highly exothermic reactions** with the organic electrolyte.
-  Release severity depends heavily on the specific **cathode chemistry**.

## Thermal Runaway Onset Temperature



*\*Relative comparisons only. Specific thresholds vary by design, state of charge, and heating rate.*

NCA and NMC are more prone to combustion than LFP due to lower oxygen release thresholds.



# The Cascade of Material Breakdown

*Thermal runaway is a sequential series of exothermic failures. Each stage releases heat that triggers the next, creating a self-sustaining feedback loop.*



STAGE 1

## SEI Decomposition

80°C – 120°C

Protective film breaks down  
Exothermic heat release  
Anode surface exposed



STAGE 2

## Separator Failure

120°C – 150°C

Plastic membrane melts/shrinks  
Direct Anode-Cathode contact  
Internal short circuit



STAGE 3

## Cathode Breakdown

150°C – 200°C+

Oxide structure collapses  
Oxygen release occurs  
Rapid heat acceleration



STAGE 4

## Full Combustion

**Peak Runaway**

Electrolyte oxidation  
Venting and pressure rise  
Toxic gas & fire hazard

**POINT OF NO RETURN: Typically reached during Stage 2/3 transition**




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# Thermal Abuse Triggers **Internal Thermochemical Cascade**

 Exposing cells to temperatures beyond safe operating limits.

 External heat initiates **SEI decomposition**, activating internal reactions.

 Once internal reactions dominate, the cell becomes **self-heating**.

 This is the primary mechanism for **runaway propagation** between cells.

## COMMON EXTERNAL SOURCES



Nearby Fire



Cooling Failure



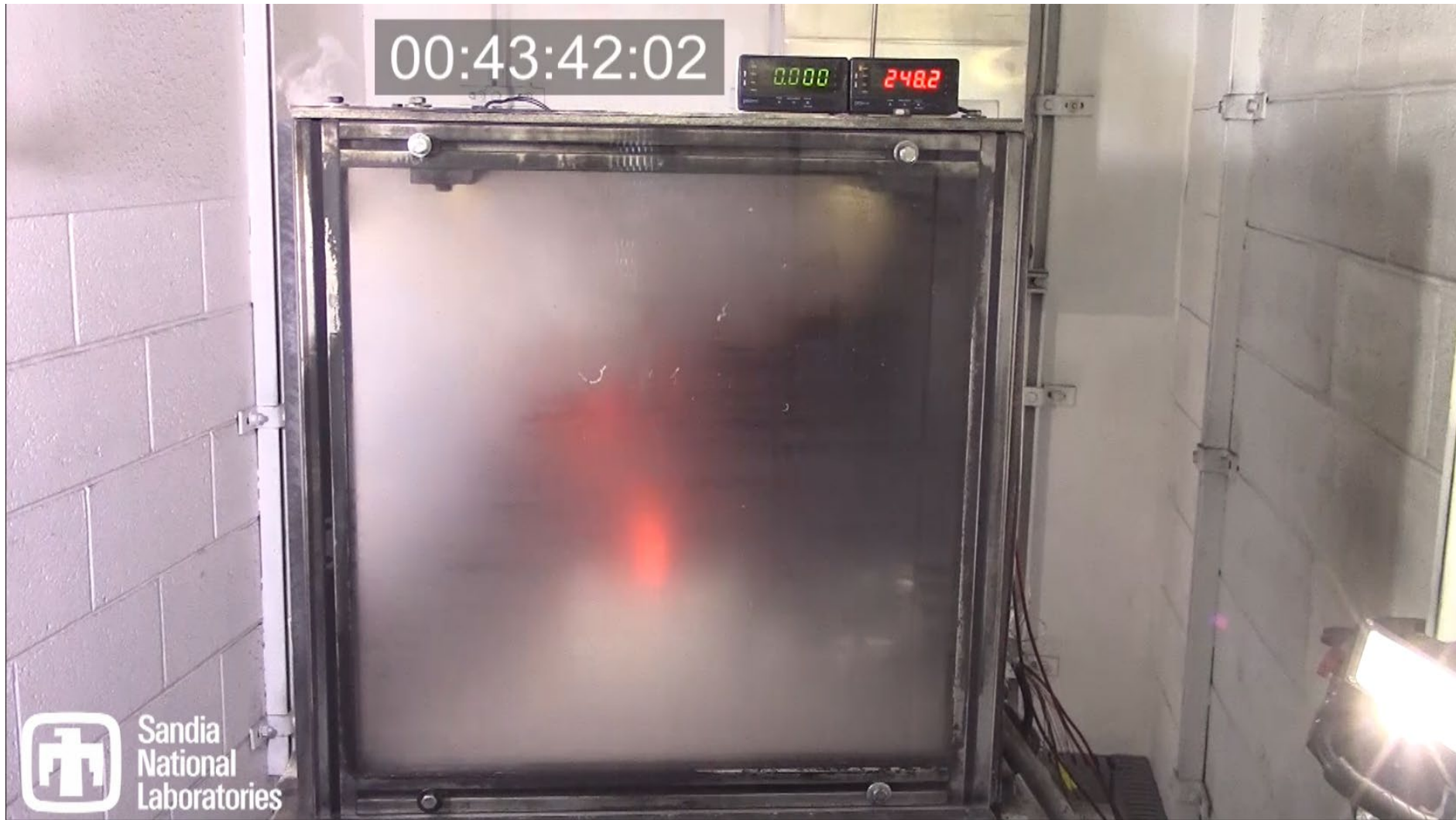
Neighboring Cell Runaway



Extreme Ambient Heat



# Thermal Ramp



# Electrical Abuse Triggers **Chemical Instability and Structural Failure**

*Exceeding voltage limits forces materials into reactive states that bypass normal safety margins.*

## Overcharge Hazards

Excess Li forms reactive metallic layers on the anode surface.

Dendrites (metallic "needles") can pierce the separator, causing internal shorts.

Over-delithiation lowers the oxygen release temperature threshold.

## Overdischarge Hazards

Deep discharge causes the anode current collector to dissolve into electrolyte.

Dissolved copper redeposits during recharge, creating conductive bridges (copper dendrites).

Short circuit often triggers during subsequent charging cycles.

**The Battery Management System (BMS) is a foundational safety component, not just a performance tool.**



# Overcharge



# Nail Penetration



# Mechanical Deformation Triggers **Instant Energy Release**



## Structural Collapse

Physical deformation—crushing, bending, or penetration—forces the anode and cathode into direct contact by destroying the separator.



## Instant Internal Short Circuit

At high State of Charge (SOC), the stored chemical energy is converted to heat (Joule heating) almost instantaneously at the point of contact.



## Localized Thermal Initiation

Intense localized heating can bypass early-stage instabilities (like SEI breakdown), triggering immediate cathode decomposition.

### COMMON FAILURE SCENARIOS

 **Vehicular Accidents & Impacts**

 **Improper Installation/Handling**

 **Seismic or Structural Events**

 **Manufacturing Defects**



*"Mechanical abuse is unique because it forces the cascade to jump directly to the most energetic stage."*



# All Abuse Modes Converge into a **Unified Internal Failure Cascade**



## Thermal Abuse

External heat drives internal temperature directly to the SEI decomposition threshold (~80°C).



## Electrical Abuse

Overcharge/discharge causes lithium plating or copper dendrites, leading to internal shorts.



## Mechanical Abuse

Physical crush or penetration collapses internal layers, causing instantaneous energy release.



## THE CONVERGENCE POINT

Self-Accelerating Heat Generation exceeds Dissipation

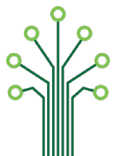
**POINT OF NO RETURN**

## SHARED MATERIAL BREAKDOWN

SEI Layer Disintegration  
Separator Melting & Massive Internal Short  
Cathode Decomposition & Oxygen Release

## SAFETY IMPLICATION

*Regardless of the initiating event, the cell's internal chemistry dictates the final hazard severity. Mitigation must address the cascade itself."*



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# LFP Chemistry: Improved Stability is **Not Total Immunity**

## Enhanced Stability (LFP)

- The **phosphate bond** holds oxygen more tightly than metal oxides.
- Higher thermal onset temperatures for cathode decomposition.
- Lower peak heat release rate during failure events.
- Reduced tendency for self-sustained oxygen release.

## Persistent Hazards

- Still contains **flammable organic electrolyte** solvents.
- Stores significant chemical and electrical energy.
- Can still vent, produce toxic or flammable gases, or ignite under abuse.
- "More stable" does not equal "stable under all conditions."



### Safety Assessment Reality Check

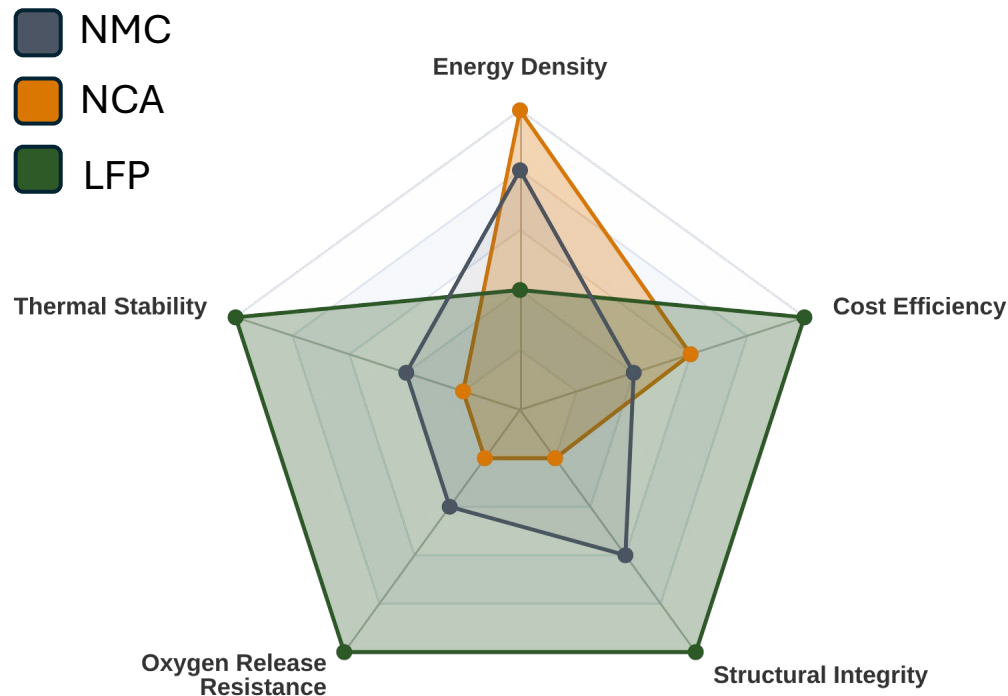
LFP reduces the likelihood of a self-sustained fire, but the hazard of toxic gas release and overpressure remains significant for indoor ESS installations.



# Beyond LFP: Every Chemistry Has a Profile

Balancing energy density with inherent thermal stability

Qualitative Comparison of Cathode Chemistries



## ⚡ NCA / High-Ni NMC

- Highest energy density for long-range applications
- Lower structural stability at high temperatures
- Higher tendency for lattice oxygen release

## 🛡️ LFP (Lithium Iron Phosphate)

- Exceptional thermal and structural stability
- Phosphate bonds hold oxygen tightly
- Tradeoff: Lower specific energy/density

## ⚖️ The Engineering Reality

*"Safer" does not mean "immune." All chemistries require robust system-level management to mitigate thermal runaway risks.*



# What About Sodium-ion?



Lithium-ion and Sodium-ion have analogous materials

## Lithium-ion

### *Cathodes:*

- Layered Metal Oxide (NMC, NCA)
- Iron Phosphate (LFP)

### *Separator*

- Polypropylene
- Polyethylene

### *Electrolyte*

- $\text{LiPF}_6$
- Carbonate and Ether Solvents

### *Anodes*

- Graphite
- Silicon



## Sodium-ion

### *Cathodes:*

- Layered Metal Oxide (NMF, NCO)
- Iron Phosphate (NFPP)

### *Separator*

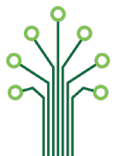
- Polypropylene
- Polyethylene

### *Electrolyte*

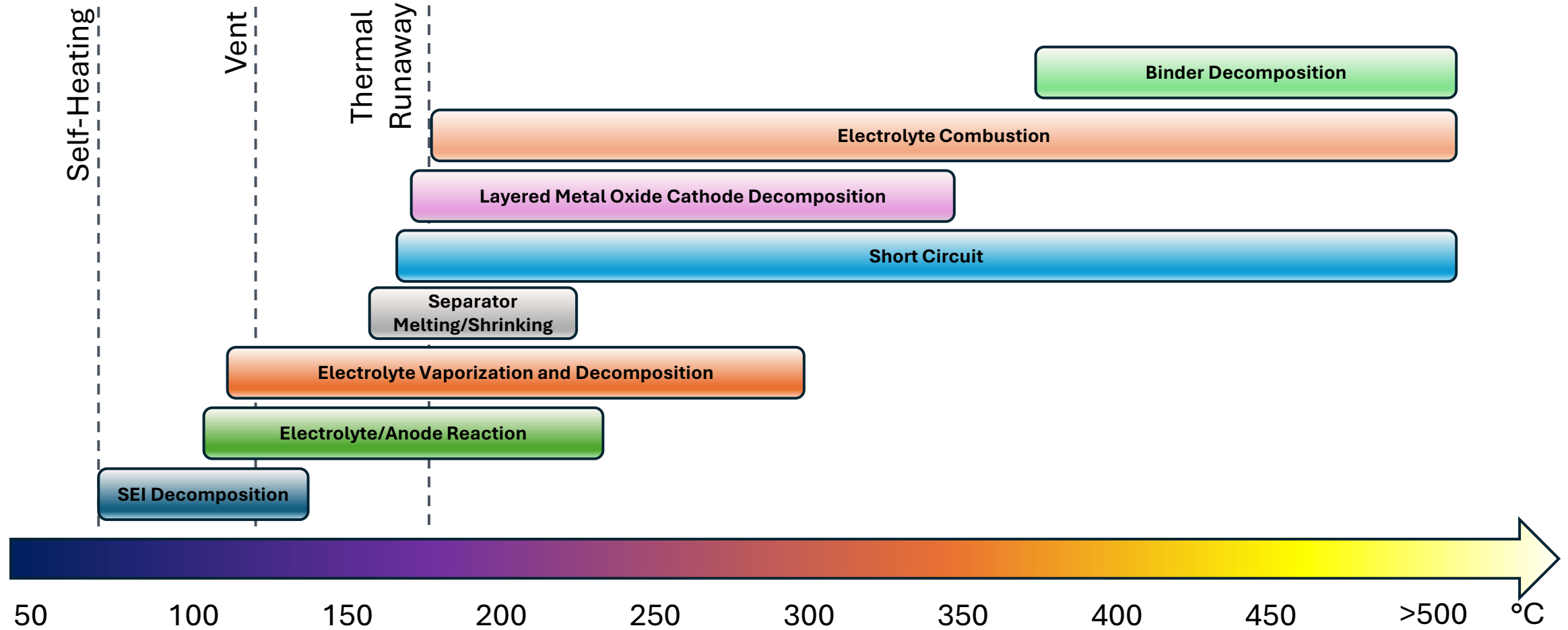
- $\text{NaPF}_6$
- Carbonate and Ether Solvents

### *Anodes*

- Hard Carbon
- Tin



# Sodium-Ion Has The Same Thermal Runaway Mechanism



# Scrutinizing Safety Claims: **Beyond "Non-Flammable" Labels**

Not all safety data is created equal—context and methodology are critical.

## Specific Testing Conditions

Evaluate the environment of the claim. Was the material tested in isolation or within a high-energy density environment?

- ✓ Temperature ranges
- ✓ Pressure variables

## Standardized Protocols

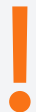
Claims must be backed by recognized industry standards (e.g., UL, IEC) rather than proprietary internal methods.

- ✓ Repeatable metrics
- ✓ Peer-reviewed data

## Full-Cell Performance

Verify that "stable" components do not introduce new failure modes (e.g., gas generation) when integrated into a complete cell.

- ✓ System interaction
- ✓ Real-world cycling



**Scientific Caution:** Be wary of absolute terms like "fireproof" or "intrinsically safe." Safety is a function of design, chemistry, and rigorous testing conditions.



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# Vented Gases Create Toxic and Explosive Risks Even Without Visible Fire

## Venting Mechanism

Cell pressure rises until the vent or seal fails, releasing high-velocity gas and vapor.

## Hidden Toxicity

Gases like HF are toxic and corrosive, posing immediate hazards to first responders.

## Explosion Potential

H<sub>2</sub> and CO can build up in enclosures and trigger delayed deflagrations if ignited.

H<sub>2</sub>

**FLAMMABLE**

Hydrogen

*High buoyancy, wide explosive range*



CO

**TOXIC & FLAMMABLE**

Carbon Oxide

*Asphyxiant, often produced in high volumes.*



HF

**HIGHLY TOXIC**

*Corrosive, penetrates skin, attacks bone.*



Vapors

**ENVIRONMENTAL**

*Flammable mist, contributes to fire spread.*



## Critical Safety Insight

No flames does not mean the area is safe; gas hazards can persist, especially with poor ventilation.



# The Hazard Is Bigger Than the Flame

Thermal runaway produces multiple hazard domains requiring unique mitigation.



## Fire

Visible combustion of electrolyte and gases. High radiant heat can drive propagation to neighboring cells.



## Smoke & Particulates

Reduces visibility for responders and can leave conductive soot deposits on sensitive electronics.



## Toxic & Flammable Gas

Venting can occur without fire. Gases may be toxic (HF, CO) or form explosive mixtures in enclosed spaces.



## Overpressure

Rapid gas generation in sealed enclosures can cause structural failure or violent "projectiles" if not vented.



**Safety design must address ALL domains: Suppression is not the same as gas management.**



# Material Mitigation Strategies: Engineering Out the Risk



## Advanced Separators

- ✓ **Ceramic Coatings:** Prevents physical contact between electrodes at high temperatures.
- ✓ **Thermal Shutdown:** Pores close automatically to stop ion flow when heat thresholds are reached.
- ✓ **Shrinkage Resistance:** Maintains structural integrity up to  $\sim 200^{\circ}\text{C}$ .



## Stable Electrolytes

- ✓ **Flame Retardants:** Organic phosphorous additives reduce the flammability of solvents.
- ✓ **SEI Stabilizers:** Additives that create a more robust protective layer on the anode.
- ✓ **Non-Flammable Salts:** Transitioning to salt systems with higher thermal decomposition points.



## Cathode Engineering

- ✓ **Surface Coatings:** Nanometer-thin metal oxide layers inhibit oxygen release.
- ✓ **Doping:** Modifying the crystal structure to improve lattice stability during heating.
- ✓ **LFP Transition:** Utilizing iron-phosphate chemistries for inherently lower oxygen release.



# From Cell Materials to ESS System Safety

Material-level insights drive robust engineering controls and system protections.

## BMS Controls

- ✓ Prevents electrical abuse (overcharge)
- ✓ Monitors thermal thresholds (SEI stability)
- ✓ Acts as a primary safety component

## Physical Spacing

- ✓ Mitigates thermal abuse propagation
- ✓ Prevents "domino effect" between cells
- ✓ Engineered thermal isolation barriers

## Suppression

- ✓ Manages the hazard domains (fire/gas)
- ✓ Cools adjacent cells to stop cascade
- ✓ Advanced detection of venting gases



The Safety Bridge: We cannot engineer system safety without knowing the material thresholds of the cells inside. System-level protection is the final layer of defense for the cell's internal chemistry.



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# Safety Starts with Science: **Thermal Runaway Fundamentals**

## **The Core Mechanism**

Thermal runaway is a self-accelerating heat balance failure. It is a positive feedback loop where internal heat generation exceeds dissipation capacity.

## **The Material Cascade**

Failure is a predictable sequence: SEI decomposition (80-120°C) → Separator failure → Cathode oxygen release → Electrolyte combustion.

## **Diverse Triggers, One Path**

Thermal, Electrical, and Mechanical abuse modes differ in initiation but converge on the same internal exothermic chemical breakdown.

## **Material-to-System Safety**

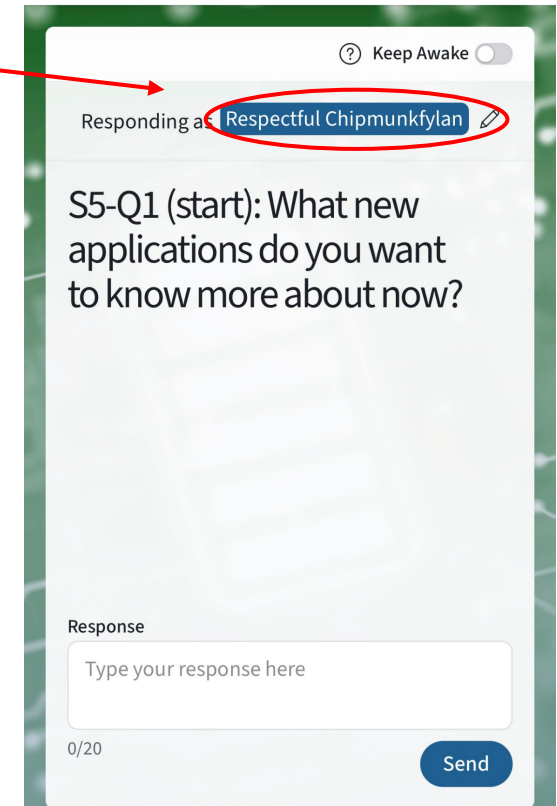
System resilience depends on cell chemistry (e.g., LFP vs Oxide) and engineering barriers to prevent cell-to-cell propagation.



# Poll Questions

Please visit Poll Everywhere via the **QR** code below (mobile) or at **pe.app/essrf** (laptop). If you would like to add your name, please update with the “**pencil**” icon. If not, feel free to remain anonymous

Respond at  
**pe.app/essrf**



# Polling Questions



1. A cell can go into thermal runaway without catching fire.
  - a) True
  - b) False
2. Heat generation primarily comes from reaction between the cathode and the electrolyte (i.e. electrolyte combustion).
  - a) True
  - b) False
3. Which event initiates self-heating?
  - a) Electrolyte reacting with the anode
  - b) SEI decomposition
  - c) Electrolyte decomposition
  - d) Oxygen evolution from the cathode
4. Which cell chemistries are inherently safe?
  - a) LFP
  - b) Na-ion
  - c) Non-flammable electrolytes
  - d) All of the above
  - e) None of the above
5. Which of the following is not a common thermal runaway initiation method?
  - a) Optical
  - b) Mechanical
  - c) Electrical
  - d) Thermal
6. Safety can be engineered at which level:
  - a) Materials
  - b) System
  - c) Both a and b
  - d) Neither a nor b



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● **THANK YOU**

