Evaluating the Safety of 1K Systems

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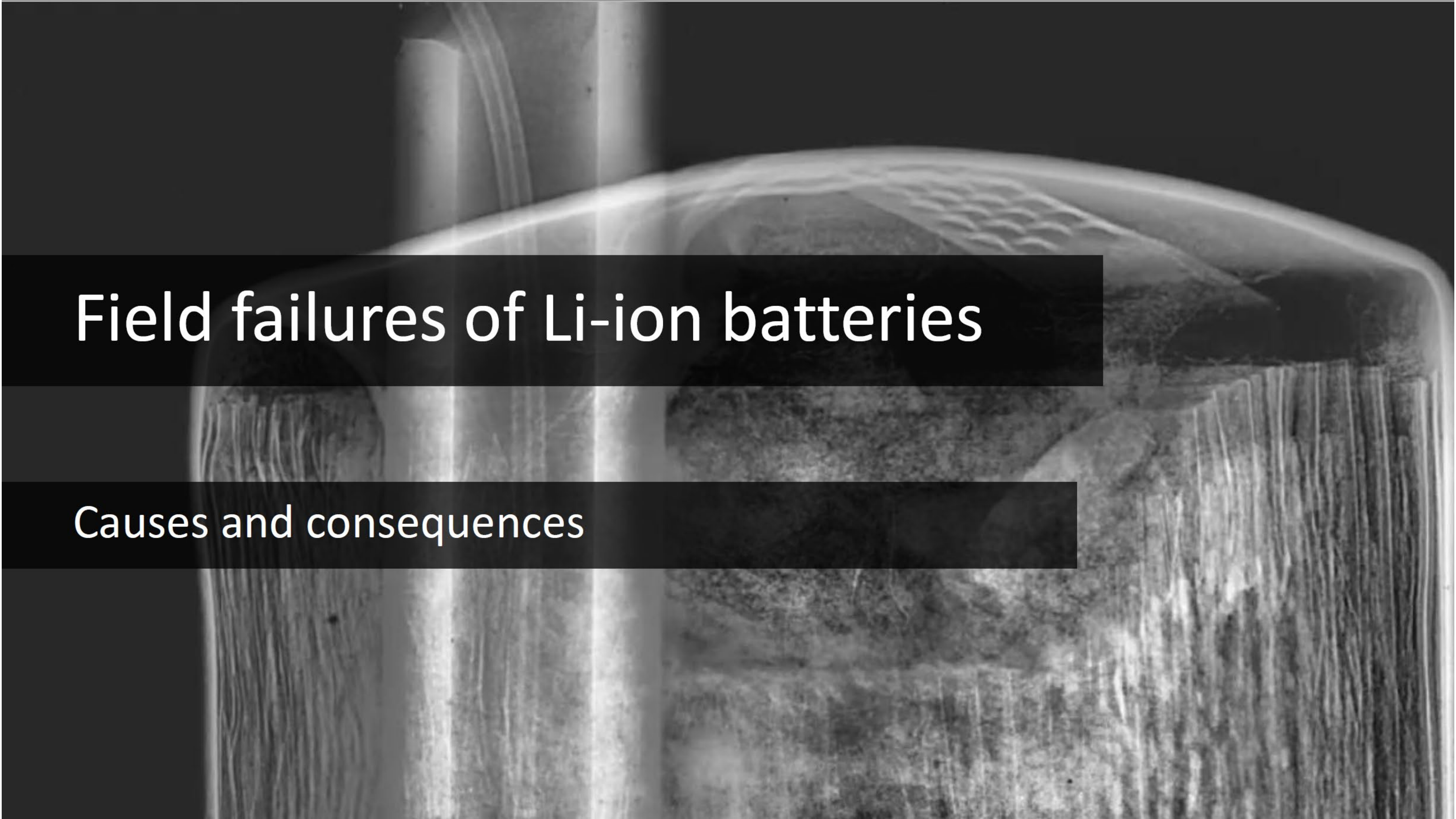
National Renewable Energy Laboratory,
Propel 1K meeting, Jul 2025

Content



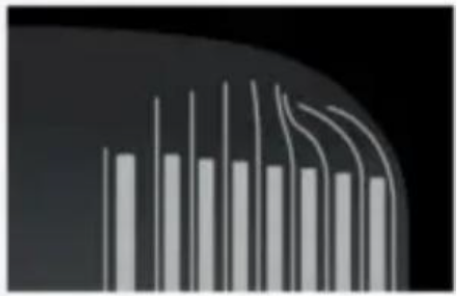
Field failures of Li-ion batteries

Causes and consequences

Notable Li-ion incidents

Incident	What happened?
Samsung Galaxy Note 7 Recall (2016)	Manufacturing flaws caused internal shorts
Boeing 787 Dreamliner Grounding (2013)	Cell internal shorts and inadequate containment
Victorian Big Battery Fire – Australia (2021)	Coolant leaked onto battery packs causing shorting
EV fires after hurricane Helene (2024)	Salt-water and high-voltages may have led to corrosion issues and shorting

Consequences: Casualties, high costs, shaken confidence, set-backs



Credit: https://www.bbc.com/news/business-38714461

Credit: https://abcnews.go.com/US/lithium-batteries-spark-catastrophic-plane-fires-faa-warns/story?id=36816040

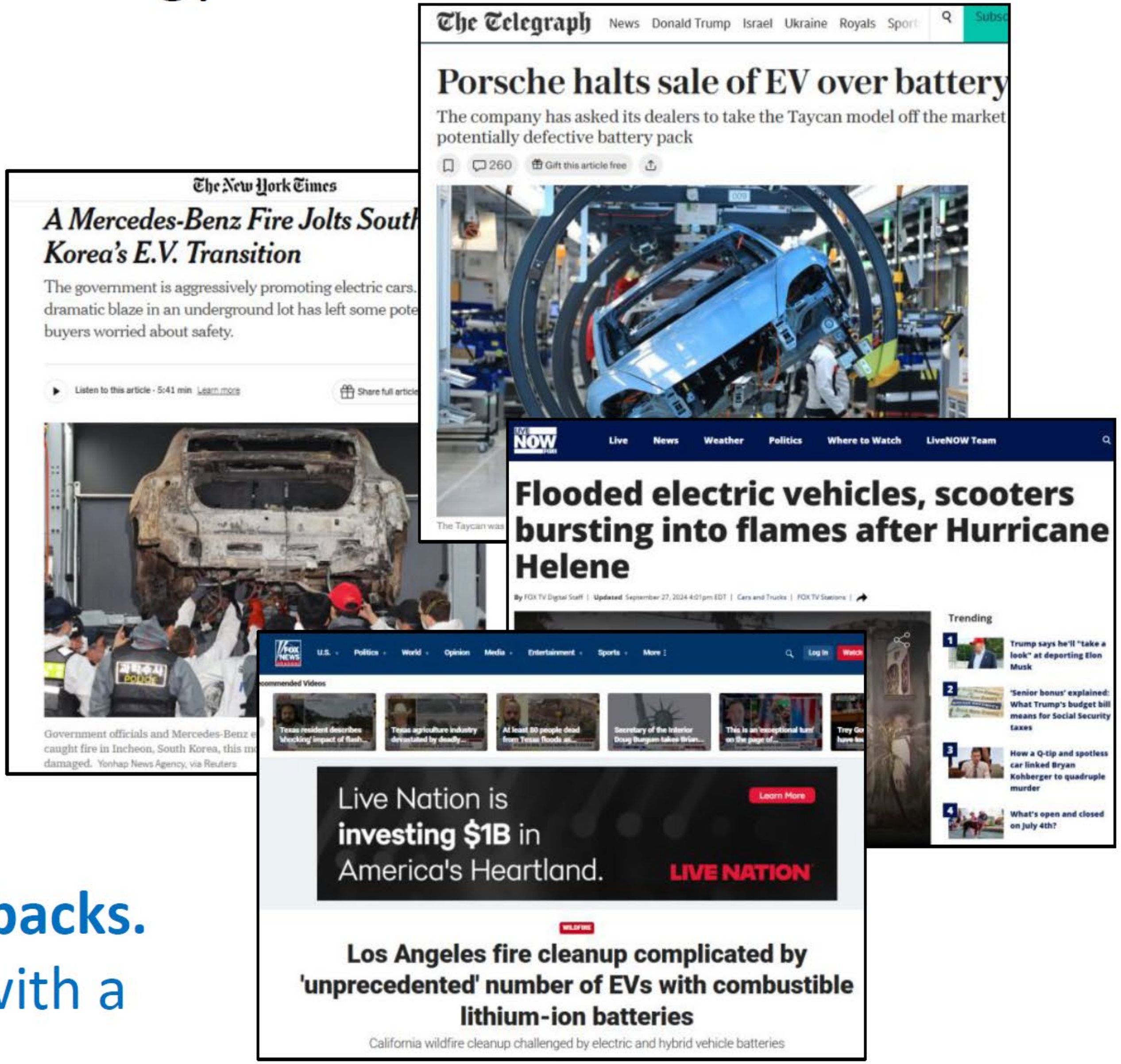
Credit: https://www.abc.net.au/news/2021-09-28/fire-at-tesla-giant-battery-project-near-geelong-investigation/100496688

Credit: https://www.eenews.net/articles/why-6-flooded-evs-burst-into-flames-after-hurricane-ian/

Challenges facing new technology

The added challenge of a new technology..

- Unseating the incumbent
- Customer confidence, risk tolerance, and lack of understanding
- Publick fear and backlash due to mistakes early in deployment
- Fear of the unknown..

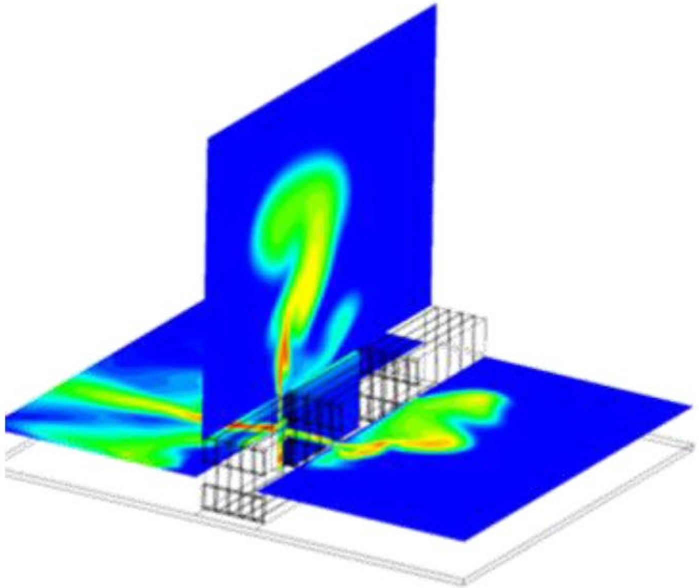


Safety incidents can lead to major set-backs.

Prepare. Design and operate systems with a focus on safety.

How to manage risks

Quantifying hazards and understanding what causes them



Quantifying hazards.. a daunting task

Total heat generated

Total gas generated

Changes in behavior with cycle history

Changes in behavior with state of charge

Properties of particulates and solids from thermal runaway

Quantifying hazards

Rate of heat generated

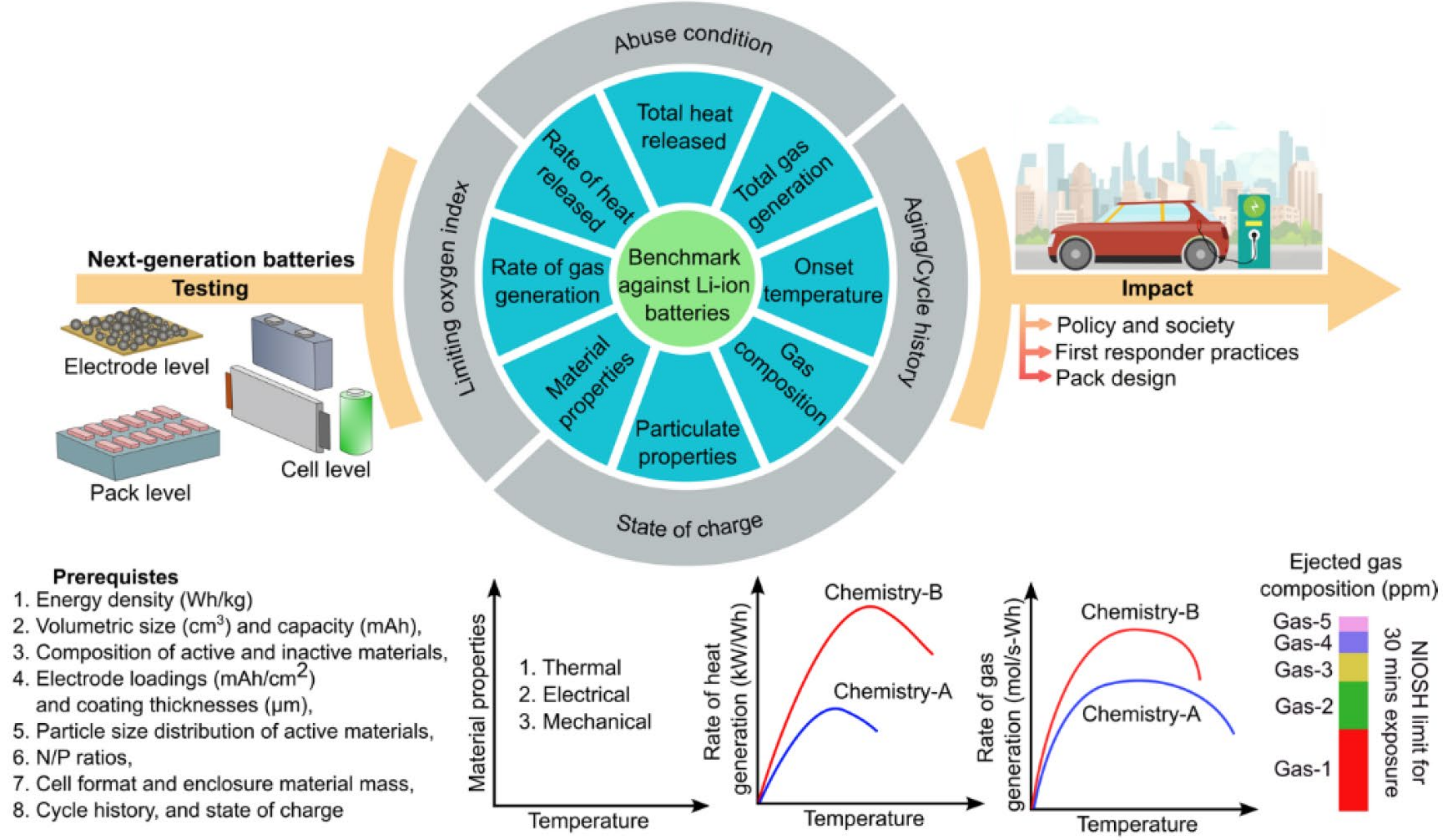
Rate of gas generated

Abuse tolerance, mechanical, thermal, electrical

Composition of gases (flammability and toxicity)

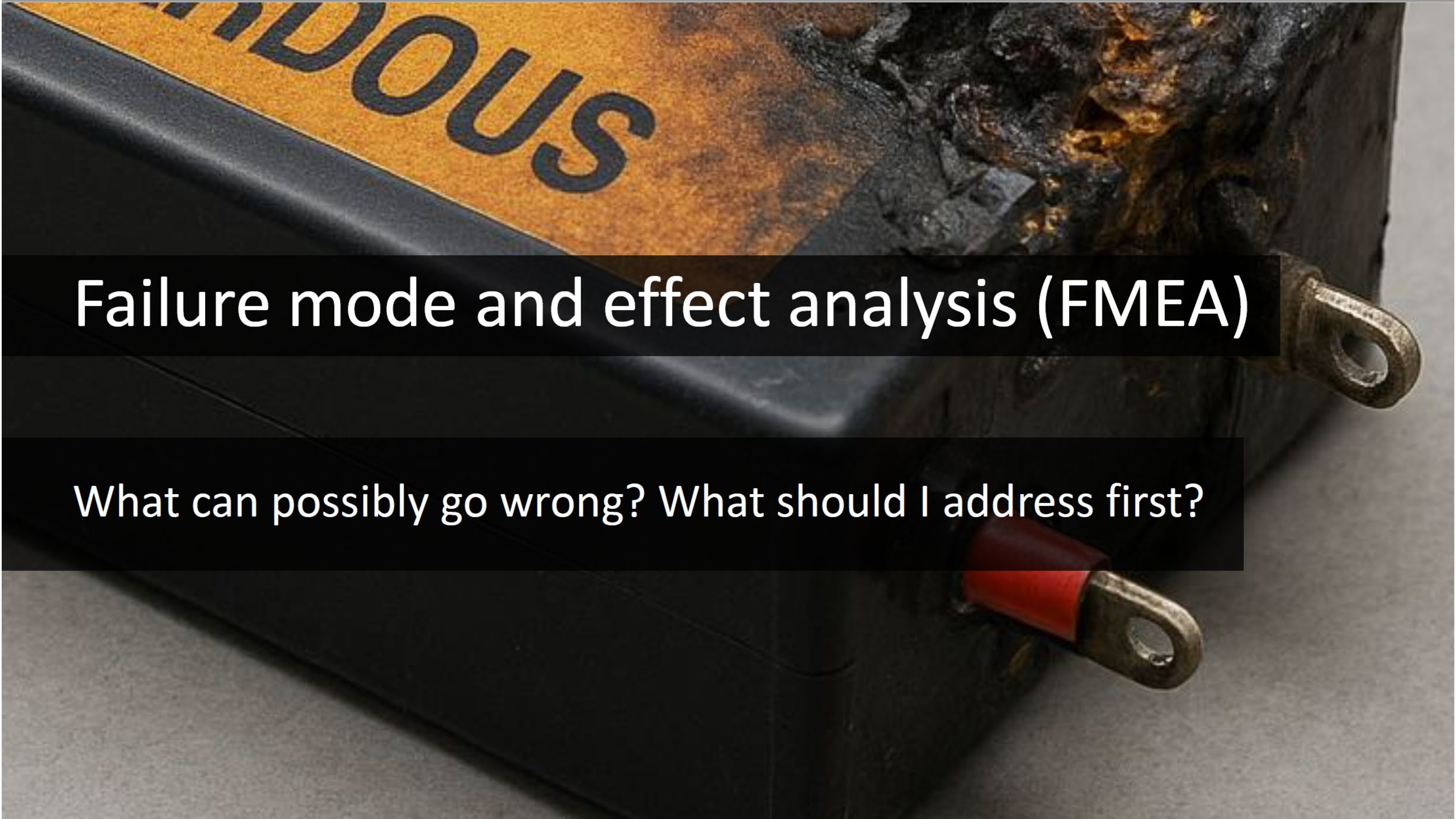
Solution: Prepare and conduct a comprehensive test campaign.

A comprehensive testing campaign



Question: This is a time-intensive and costly effort, how can I prioritize?

Yang et al. Addressing the safety of next generation cells, Nature, in press



Failure mode and effect analysis (FMEA)

What can possibly go wrong? What should I address first?

Failure mode and effect analysis (FMEA)

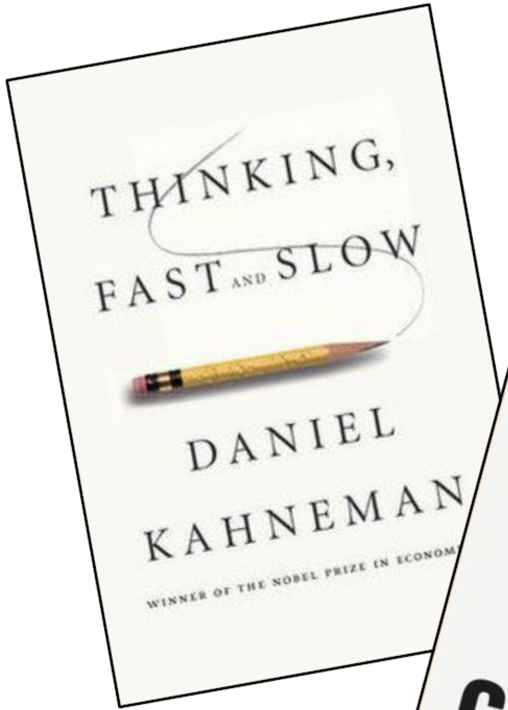
What can possibly go wrong?

- **Team exercise:** Brainstorming together is valuable for collectively identifying challenges and improving systematic understanding
- **Guided thought process:** Structure of FMEA guides you to think about what can happen under a range of operational or non-operational conditions
- **Knowns:** Describe the known failure modes and hazards
- **Unknowns:** Likely to be many for technologies that are not yet established
- **Inherent prioritization:** Ranking system helps identify priority challenges to address

Function	Potential Failure	Effect	Severity	Potential cause of mechanisum of Failure	Occurrence	Current method of Detection/control (EV Field)	How Good is the detection	Revised RPN	Recommended Actions	Notes
Operational condition and environment (e.g. slow charging in cold temperatures)	What can happen? (e.g. loss of function or intermittent function)	Fire	1 to 10	What could cause the failure?	1 to 10	Describe what could detect the flaw in today's systems (e.g. voltage sense in BMS)	1 to 10	1 to 1000	What action is needed to mitigate?	Any other thoughts and notes.

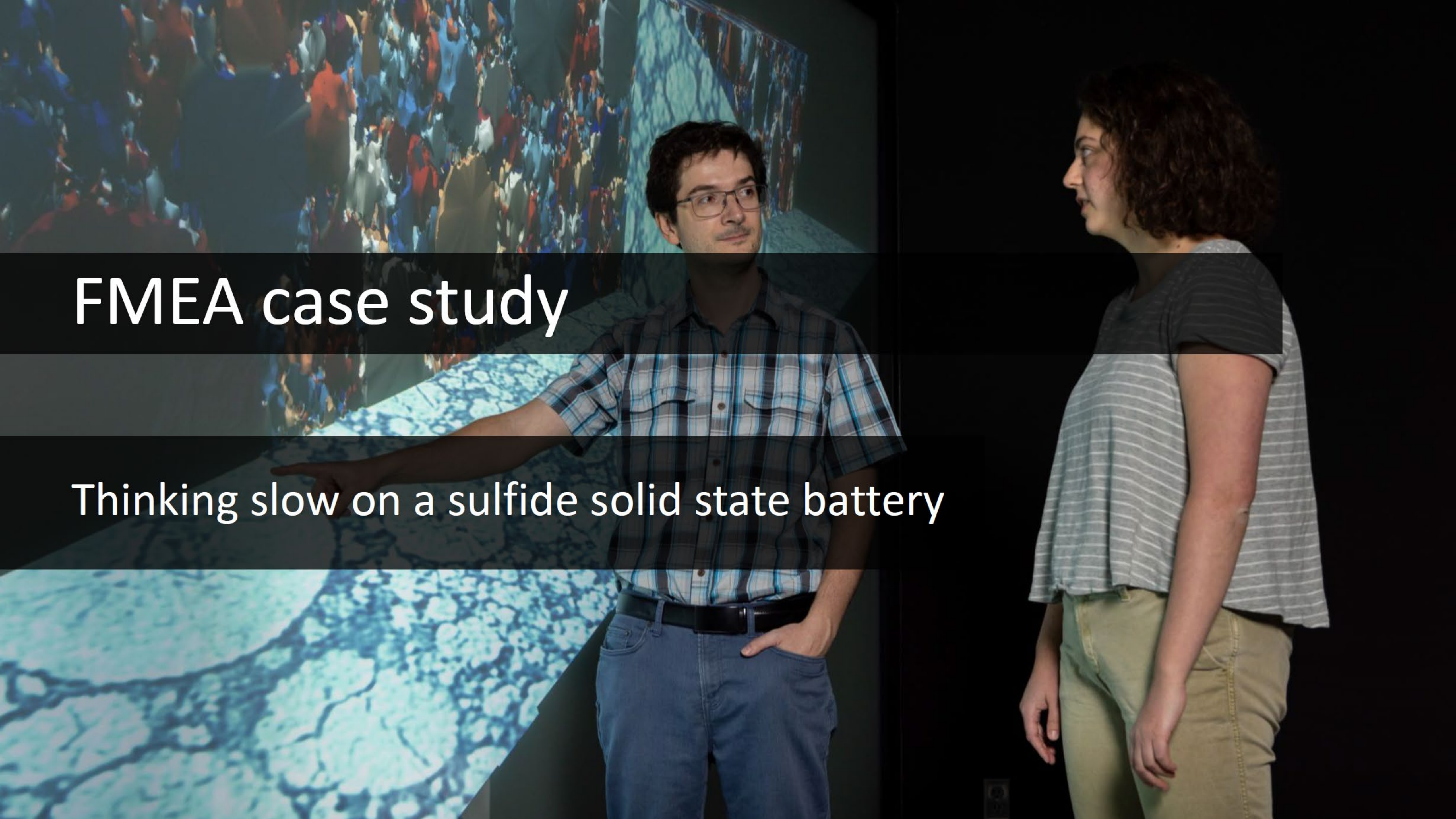
Think slow.. review, interpret, plan

- **Review:** At the end of the FMEA process, review the functions, failure modes, and effects. Is there anything missing? Have you addressed likely conditions that arise in the field?
- **Interpret:** Are there disparate failure conditions that relate to common design features? Is there a particular vulnerability that arises from your manufacturing? Are there operating conditions that should be avoided?
- **Plan:** What actions can you take? Can the manufacturing process be amended? Can the controlling measures address some failure conditions? What are the unknowns that need to be evaluated and how can you evaluate them?



FMEA case study

Thinking slow on a sulfide solid state battery



FMEA: Sulfide solid-state

Root causes of top RPN scores

1. **Failure of the solid separator**, either from dendrites and/or chemical degradation of its mechanical integrity or electrical insulative properties.
2. **Li plating and side reactions** that can occur during fast charge or cold charge conditions.
3. **Heterogeneous ionic conductivity** within electrolyte that leads to regional overuse or under use.
4. **Chemical degradation of electrolyte** where the electrolyte loses its ionic or electronic conductivity
5. **Heterogeneous material activity** that leads to overuse of some regions of the electrode and accelerates capacity fade and dendrites.
6. **Uneven compression within the cell**, either by external or internal operational forces.

Top RPN scores

Function	Potential Failure Modes	Mechanism	Occurrence	Mode	Effect	Severity	Current Method of Detection/ Control	Detection	RPN (Risk priority number)	Comments
Cycling	1	Break-up of separator and electrolyte via interfacial reactions, dendrites, cyclic mechanical stresses	8	increase in electrolyte resistance, higher risk of dendrites	Internal short circuit, thermal runaway, reduced abuse tolerance	9	None	8	576	Unique to SSBs
Fast charge	1	Li Plating / Dendrite growth. Additional SEI growth on plated lithium.	6	Loss of lithium inventory	Internal short circuit, thermal runaway, capacity fade	9	None	10	540	
Fast charge	2	Uneven ionic conductivity within separator and cathode	8	Over or underutilization of regional active material	Capacity fade, resistance rise, self heating	6	None	10	480	Unique to SSBs
Cycling	2	Chemical degradation of electrolyte	10	Loss of ionic conductivity	Power fade	6	None	8	480	
Cycling	2	Increasingly heterogeneous utilization	10	Formation of hot spots, over- and under-utilization	Capacity fade, power fade, self heating	6	None	8	480	Unique to SSBs
Charge	2	Uneven compression from anode expansion during lithiation	6	Heterogeneous lithium content, lithiation gradients, overused cathode particles	Capacity fade, self heating	6	None	10	360	Unique to SSBs

FMEA: Sulfide solid-state

Key insights that are unique from Li-ion

Notable opportunities:

- Sulfide solid-state have **improved thermal stability** compared to solvent-based electrolytes. This is expected to facilitate higher temperature storage and operational conditions while avoiding electrolyte evaporation.
- Sulfide solid-electrolytes are **expected to have reduced gassing** from evaporation or side-reactions compared to solvent-based electrolytes, therefore no ionic isolation due to electrolyte "dry-out".
- Sulfide solid-state have **improved mechanical abuse tolerance** and lower likelihood for thermal runaway upon impact.

Notable challenges:

- **Manufacturing process is different** from conventional Li-ion, and therefore a manufacturing focused FMEA should be conducted.
- **Heterogeneous material properties** are a concern, such as uneven ionic conductivity from uneven pressure in the electrode microstructure. Related to heterogeneous properties is **heterogeneous utilization of materials.**
- **Mechanical weakening of solid separator** materials over time and cycling is an unknown but likely greater in magnitude that polymer separators.
- **Changing ionic conductivity properties** of electrolyte over time and cycling is currently unknown.
- **Uneven internal forces** accruing due to heterogeneous lithiation or heterogeneous microstructures from manufacturing.

FMEA: Sulfide solid-state

(green)	Capability exists in vehicle
(beige)	Does not exist in vehicle

Solutions to address notable challenges

Refining process conditions and developing methods to measure **heterogeneous materials properties** can reduce heterogeneities during manufacturing.
Operational conditions can be controlled to reduce **heterogeneous utilization** such as by keeping operational rates low and controlling a uniform temperature throughout the battery pack.
Uneven forces within a cell could be alleviated by incorporating isostatic pressure on the outside of the cells and manufacturing cell materials with increased elasticity to achieve isostatic pressure within the cell.
To address **degrading mechanical and conductive properties**, the operational protocol of the cell could be changed throughout the cells life to become less demanding and to reduce the risk of capacity fade.

Major fault description	Possible vehicle diagnostics
Heterogeneous material utilization	Current pulses and voltage relaxation
Loss of mechanical integrity of materials	Acoustic monitoring
Loss of ionic conductivity of materials	Differential voltage, impedance measurements

Research topics to address unknowns

Better understand spatially heterogeneous degradation rates in SSBs
Better understand the changing material properties of solid electrolytes with time and cycling
Heterogeneity of internal forces with time and cycling
Prevalence and consequences of manufacturing defects for specific manufacturing processes, e.g. Slurry casting, dry-process lamination, compaction

ARPA-E EVs4ALL

Removing barriers to market through understanding the safety of new technologies

EVs4ALL Program

EVs4ALL overview

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Teams:

1. **NREL**, UT Austin, Exponent
2. **Sandia**, UMD, Purdue, UL

Project goal: NREL and Sandia aim to determine the hazards and abuse tolerance of next-generation batteries, provide guidance on standard testing methods for evaluating the safety of next-gen cells, and to identify opportunities to manufacture safer battery systems

NREL's project partners

- Ampcera
- Project K
- Tyfast
- Virginia Tech
- WHPower
- 24M

Sandia's project partners

- Zeta Energy
- South 8
- University of Houston
- Solid Power
- Ohio State University
- University of Maryland

Key deliverables

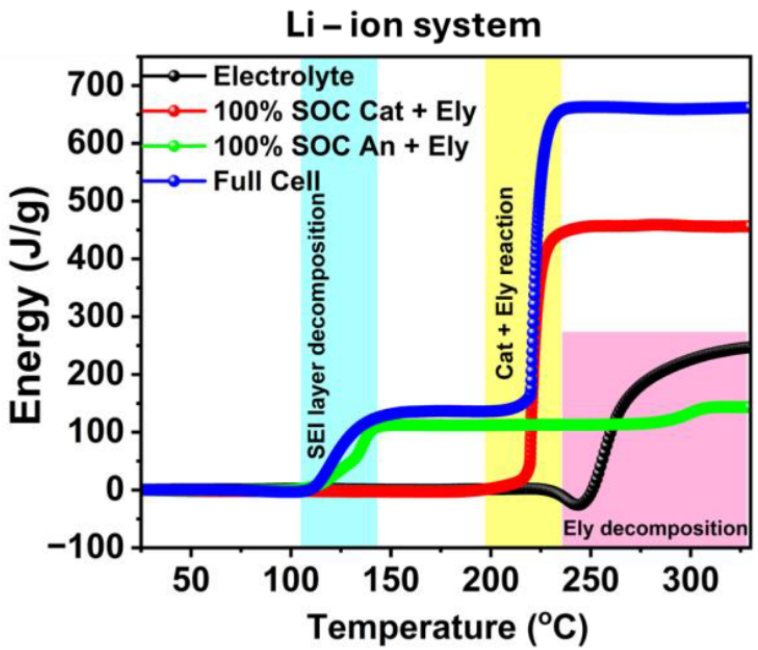
1. **Energy release diagrams** for each partner technology
2. **FMEA** for each partner technology
3. **Standard testing manual** for evaluating risks of next-generation cells

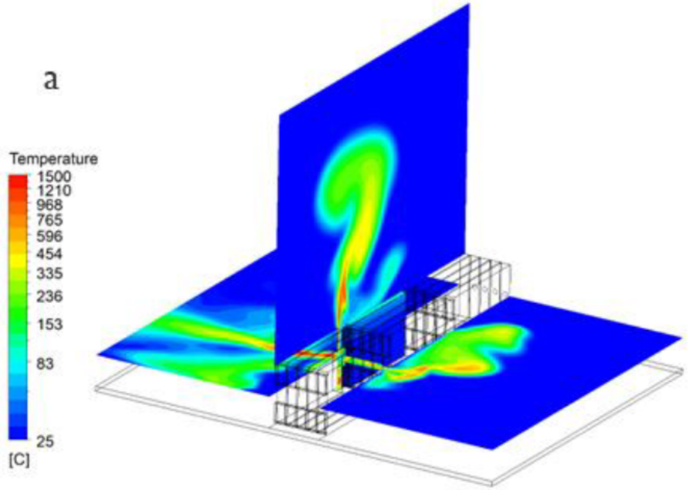
Resources at NREL and Sandia

National labs have state-of-the-art facilities to help with:

- **Calorimetry:** Differential Scanning Calorimetry (DSC), Accelerating Rate Calorimetry (ARC), Isothermal calorimetry.
- **Emissions:** Gas and particulate analysis of emissions including gas chromatography, Fourier Transform Infrared (FTIR) spectroscopy.
- **Full cell and battery abuse testing from mWh to kWh**
  - **Mechanical abuse:** Crush, drop, puncture
  - **Electrical abuse:** Up to 1000 V and 1000 A
  - **Thermal abuse:** Low temperature (-40 °C) and high temperature (>500 °C)
- **Modelling and parameterization:** Materials paramterization (thermal, mechanical, electrical properties) and multi-scale and multi-physics modelling.

Cell heat at 100% SOC = 2.5 kJ/Wh





Conclusions

- **Risks:** Batteries have inherent safety risks that need to be managed
- **Risk Management:** Managing risks requires extensive testing to characterize failures, quantify hazards, and inform design of systems to mitigate risks.
- **Conducting an FMEA:**
  - Helps understand your product, identify vulnerabilities, and how to prioritize R&D to get-ahead on managing risks.
  - Following an FMEA, think slow: review, interpret, plan
- **EVs4ALL:** NREL and Sandia aim to reduce barriers to market by addressing safety. challenges sooner for up-and-coming energy-storage technologies.
- **Resources:** NREL and Sandia have state-of-art facilities. Please reach out.

Thank you for listening!

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NATIONAL RENEWABLE ENERGY LABORATORY

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