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Failure Mechanisms of Li-ion Batteries

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Presentation to NTSB

April 11, 2013

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Topics

- Approach & Goals for battery safety.
- Safety Characterization: Thermal, Electrical and Mechanical abuse.
- Abuse Testing vs. Field Failure.
- Describe how a thermal runaway initiates and propagates (cascading failures). Can it be stopped or controlled?
- Internal shorts versus external shorts.
- Thermal management (passive vs. active temperature control).
- Battery pack design and enclosures.
- What are the Critical Safety Concerns?

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Approach

- Safety cannot be determined or evaluated by one criterion or parameter.
- Enhanced safety is determined by the implementation of several approaches that work synergistically to achieve the goal of:
  - **Reducing the probability of a battery failure event.**
  - **Lessening the severity of outcome if an event occurs.**
- As this safety approach is applied to batteries, **thermal stability*** is perhaps the most important of several parameters that determine safety of Li-ion cells, modules, and battery packs.

***D. H. Doughty, "Vehicle Battery Safety Roadmap Guidance" (Oct. 2012, 131 pages) Available from http://www.nrel.gov/docs/fy13osti/54404.pdf**

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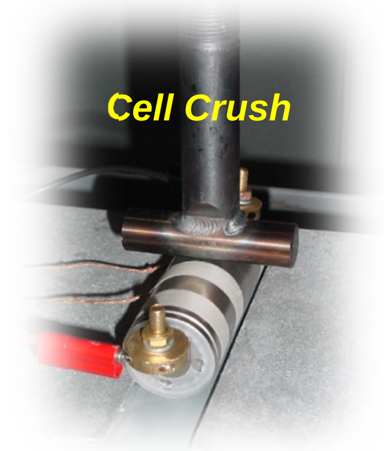
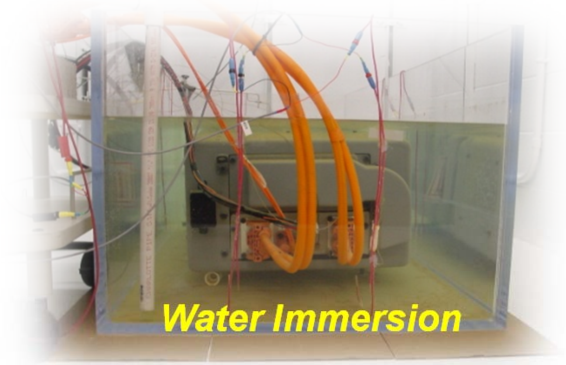
Abuse Test Response can be Systematically Investigated.

- ***Batteries area exposed to realistic “off normal conditions” abusive conditions.***
  - **Mechanical**
    - **Crush**
    - **Nail Penetration**
    - **Drop**
    - **Mechanical Shock**
    - **Vibration**
    - **Water Immersion**
  - **Electrical**
    - **Overcharge**
    - **Over-discharge**
    - **Short Circuit**
    - **Partial Short Circuit**
  - **Thermal**
    - **Overheat/Thermal Ramp**
    - **Fire**





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Comparison of Failure Modes

- There are important differences between safety abuse testing, versus field failures (*generally attributed to internal short circuit*).

Abuse Tolerance

- Predictable
- Common to all cells
- Can/should be evaluated at the cell level
- Various chemistries can/should be evaluated for relative abuse tolerance
- Time constants relatively long
- Can be augmented by protection devices

Field Failures

- Not predictable
- One-in-ten-million (or less)
- Difficult to evaluate at the cell level, or through QC
- Materials must be evaluated for relative kinetics, pressures
- Much higher temperatures can occur *quickly*
- PTC, CID, shutdown separators, electronic controls are not effective

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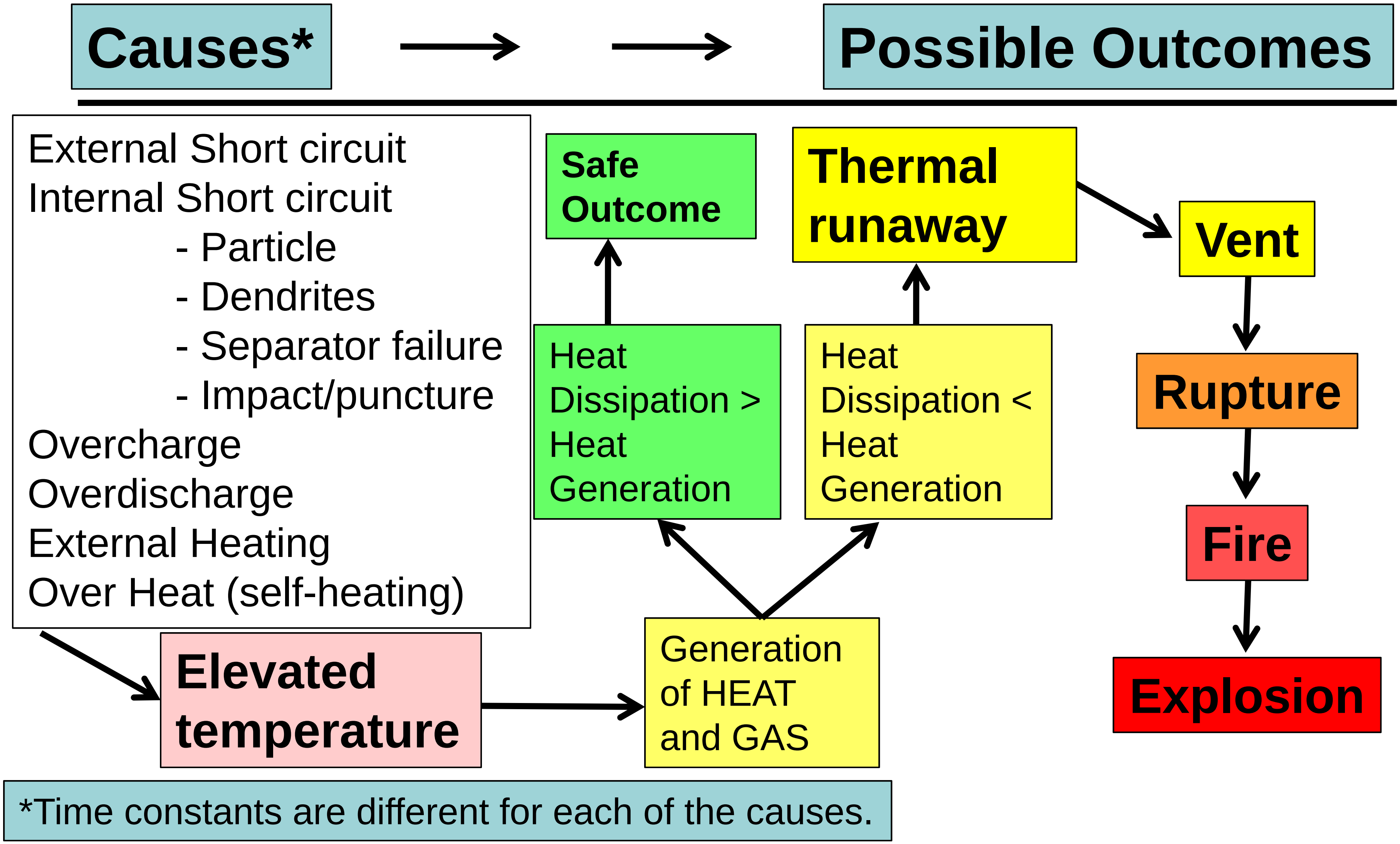
Anatomy of Cell Failure



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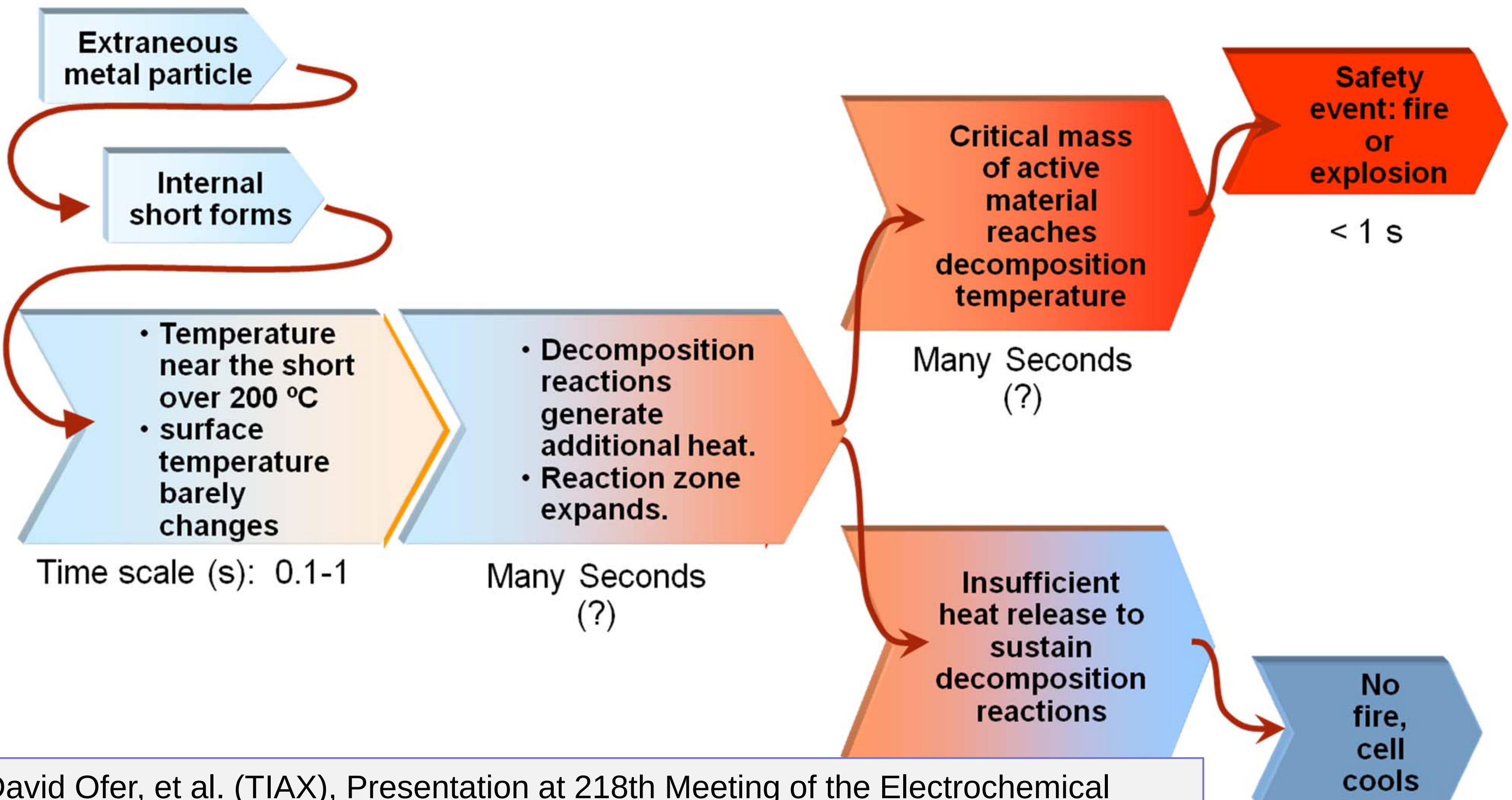
Internal Short Circuit Has Fast Kinetics for Heat & Gas Generation*

Not all internal shorts that develop in lithium-ion cells result in a thermal runaway and field-failure safety incident.



* David Ofer, et al. (TIAX), Presentation at 218th Meeting of the Electrochemical Society, Las Vegas, Nevada, October 12, 2010

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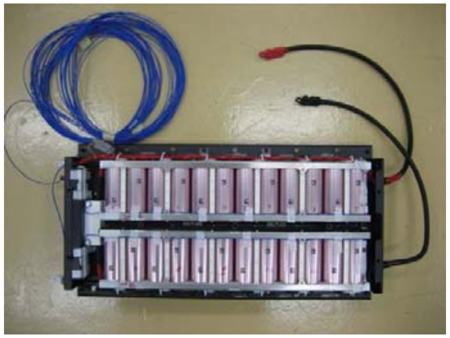
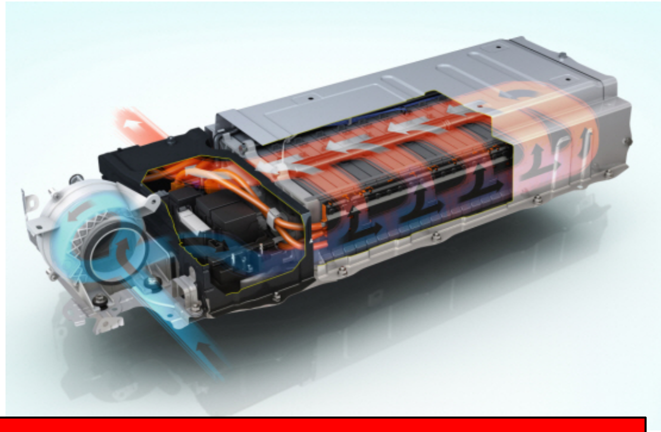
Failure Propagation

If you can't prevent or predict cell failure, it is essential to prevent propagation that leads to destruction of the module/pack.

Cell Failure → Cell Cascade Failure → **Module Failure** → Module Cascade Failure → **Pack Failure**





Response determined by intrinsic cell properties

Response determined by engineering design such as thermal management, pack engineering and electrical safety devices.

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What Are The Triggers of Thermal Runaway and How Can They Be Managed?

Trigger	Why can this occur ?	Is this managed ?
External short circuit	Defective connections, foreign debris.	Yes, cell-level safety devices and pack safety fuses.
Overcharge	Defective connections, failure of charging circuit.	Yes, battery management system. Yes, cell-level safety devices.
Overheating from external sources	Battery pack placed too close to a heat source.	Yes, cell-level safety devices open the cell at suitable internal pressure.
Cell crushing creating massive internal shorts	Physical abuse of battery pack.	Yes, design enclosures are built more tolerant to abusive events.
Internal short-circuit	Internal-short caused by manufacturing defects.	No, new technologies needed.
Propagation of thermal runaway	Affected cell can raise the temperature of surrounding cells.	Yes, in a few cases, but new technologies needed.

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Thermal Management

- Thermal management is very important for performance and safety.
  - Temperature uniformity extends useful lifetime
    - Keeps cells balanced (i.e., uniform capacity within the pack).
  - Understanding the heat generation as f(temp) and heat capacity of cells is crucial.
    - Avoid propagation of a single cell failure.
  - Temperature control design choices:
    - Passive vs. active temperature control.
    - Type of cooling (air or liquid).
    - Thermal cut-off switches, etc.

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Battery Pack Design And Enclosures

- Design guides exist for various applications:
  - RTCA DO-311 “*Minimum Operational Performance Standards for Rechargeable Lithium Battery Systems*”, Section 1.9 "Design Requirements"
  - IEEE 1625 “*IEEE Standard for Rechargeable Batteries for Multi-Cell Mobile Computing Devices*”, Section 6, “Pack considerations”
  - UL 2580 “*Batteries for Use in Electric Vehicles*”, Section 5 “Construction”.
- Recommend performing a review and incorporate “best practices” for aviation design standards.

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Summary: What are the Critical Safety Concerns?

- ***Energetic thermal runaway of active materials***
  - Exothermic materials decomposition, gas evolution, electrolyte combustion.
- ***Electrolyte degradation, gas generation & flammability***
  - Overpressure and cell venting is accompanied by an electrolyte spray which is highly flammable.
- ***Internal short circuit***
  - Internal short circuit may cause very rapid release of heat and gas.
    - Very low probability, but consequence can be high.
  - No screening tests or effective mitigation is available.
- ***Propagation***
  - Observed in field failures.
    - Laptop failures in 2006 included several explosions from a single laptop, separated by several minutes, until the entire battery pack was consumed.
  - Experimentally observed in test labs.
  - Propagation as been modeled* using Accelerating Rate Calorimetry (ARC) data as well as convective, conductive and radiative heat transfer.

*Spotnitz, Doughty et al., Journal of Power Sources 163 (2007) 1080–1086.