EXTRACT

Lithium-Ion Cell and Battery Safety

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Section 1. Background and Fundamentals of Battery Safety

- Battery Safety Fundamentals
- Examples of Recent Recalls
- Hazards & Thermal Runaway
- Cell Failures
- Safety Devices

Section 2. Understanding Battery Failure Modes

- Understanding Battery Failures
- Li-Ion Battery Safety & Abuse Characterization Tests
- Propagation of Thermal Runaway of Single Cell
- Abuse Tolerance Simulation
- Effect of Cell and Pack Design on Abuse Response

Section 3. Safety Validation: Abuse Testing Methods & Procedures

- General
- Shipping Procedures
- Pass/Fail vs. Safety Characterization Tests
- Test Procedure Comparisons
- Functional Safety
- What's Missing?

Summary and Conclusions

Appendix: Organizations that Publish Safety Test Standards

Section 1.

Background and Fundamentals of Battery Safety

- Battery Safety Fundamentals
- Examples of Recent Safety Recalls
- Hazards & Thermal Runaway
- Cell Failures
  - Causes of Cell Failure
  - Event Probability and Risk
- Safety Devices
  - Mechanical Components
  - Separator
  - BMS

What are the Critical Safety Concerns for Batteries?

Energetic Thermal Runaway of Active Materials

- Exothermic materials decomposition, gas evolution, electrolyte combustion
- Can be mitigated through new materials, coatings, additives

Electrolyte Degradation, Gas Generation & Flammability

- Overpressure and cell venting are accompanied by an electrolyte spray which is highly flammable
- Can be improved with electrolyte choices with minimal impact on performance
- Need to ensure flammability testing accurately captures this active failure event

Separator Failure & Internal Short Circuits

- Incomplete separator shutdown can lead to catastrophic failure at >135 °C
- Shutdown separators can show instabilities at high stand-off voltages (relevant to EV- and PHEV-scale modules and packs)
- Need to examine the role of non-shutdown separators

Propagation

- Observed in field
  - 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 has been modeled using Accelerating Rate Calorimetry (ARC) data as well as convective, conductive and radiative heat transfer
  - See Spotnitz, Doughty et al., *Journal of Power Sources* 163 (2007) 1080–1086

Li-Ion Cell Energy vs. TNT

- Batteries contain fuel and oxidizer in a sealed container
  - If the energy contained in a battery cell is inadvertently released in thermal runaway, there is no way to quench the reaction because the fuel and oxidizer are in intimate contact.
- Other examples: gun powder, rocket propellant, and high explosives
  - The energy content of TNT is 4.61 megajoules per kilogram (MJ/kg) which is 1280 Wh/kg. The highest electrochemical specific energy available in today's commercial Li-ion rechargeable batteries is approximately 240 Wh/kg.
  - However, when we consider the available thermochemical energy from decomposition reactions of the electrolyte, the available energy to be released under abusive conditions is about 2.5MJ/kg—54% of the energy of TNT
- Good news: once a cell enters thermal runaway, it goes to completion and self-extinguishes as reactants are exhausted
  - Allows an opportunity to apply engineering solutions to avoid propagation to adjacent cells

DOE Perspective Regarding Lithium-ion Battery Safety*

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Safety of Batteries is of Central Importance

- Safety is a key barrier to introduction of rechargeable batteries into vehicles.
  - Vehicle environment is challenging (temperature, vibration, etc.)
  - Large cells and large capacity batteries for vehicle traction present additional challenges
- Safety is a systems issue, with many inputs and factors.
  - Even "safe" cells and batteries can prove unsafe in some applications due to poor engineering implementation or an incomplete understanding of system interactions.
- Standardized tests are crucial to obtain a fair comparison of different technologies and to gauge improvements.

**David Howell, "U.S. DOE Perspective on Lithium-ion Battery Safety", Technical Symposium: Safety Considerations for EVs powered by Li-ion Batteries, May 18, 2011*

Safety Evaluation Should be Done on Many Levels

- On a component level (materials and structures inside the cell) this includes evaluation of reactivity of all materials, tests of electrolyte flammability and thermal analysis (such as differential scanning calorimetry) of electrolytes and of electrodes with and without electrolyte.
- Available with report purchase
- On a battery management system (BMS) level, determine if the electronic system manages a rechargeable battery (cell or battery pack) properly, such as by protecting the battery from operating outside its Safe Operating Area, monitoring its state, calculating secondary data, reporting that data, controlling its environment, authenticating it, and/or balancing it.

CPSC Recalls

- U.S. Consumer Product Safety Commission (CPSC) recalls:
  - See http://www.cpsc.gov/ and search for "Battery Recalls" or "Battery Fire"
- Recent postings:

Brunton Outdoors Recalls Battery Packs Due to Fire Hazard ...
The Impel and Impel 2 power packs' lithium ion batteries can overheat and catch on fire during charging.
www.cpsc.gov/en/recalls/2016/brunton-outdoors-recalls-battery-packs/ - 66k - 2016-04-22 - Cached

PNY Recalls Portable Lithium Polymer Battery Packs Due to ...
Batteries can overheat and vent flames, posing fire and burn hazards.
www.cpsc.gov/en/recalls/2016/pny-recalls-portable-lithium-polymer-battery-packs/ - 63k - 2015-11-12 - Cached

Panasonic Recalls Lithium-ion Laptop Battery Packs Due to ...
Conductive foreign material was mixed into the battery cells during manufacturing, posing a risk of fire.
www.cpsc.gov/en/recalls/2016/panasonic-recalls-lithium-ion-laptop-battery-packs/ - 63k - 2016-03-21 - Cached

Toshiba Recalls Laptop Computer Battery Packs Due to Burn ...
The lithium-ion battery packs can overheat, posing burn and fire hazards to consumers.
www.cpsc.gov/en/recalls/2016/toshiba-recalls-laptop-computer-battery-packs/ - 67k - 2016-04-13 - Cached

Pelican Products Recalls Flashlights and Replacement ...
The battery packs in the flashlights can overheat, posing a fire hazard to consumers.
www.cpsc.gov/en/recalls/2016/pelican-products-recalls-flashlights-and-replacement-battery-packs/ - 63k - 2016-03-03 - Cached

Battery Recalls in the U.S.

- Search "battery fire recall statistics" on CPSC website (http://www.cpsc.gov/en/Search/?query=&filters=recalls) finds:
  - 23 so far in 2017
  - 29 in 2016
  - 13 in 2015
  - The recall rate has increased over the last 10 yrs. (average of 16/yr.) from 2005 to 2008
- Batteries with high-energy density and large energy capacity are being fielded
- The industry still needs to improve safety

3. There were welding issues (welding burrs on

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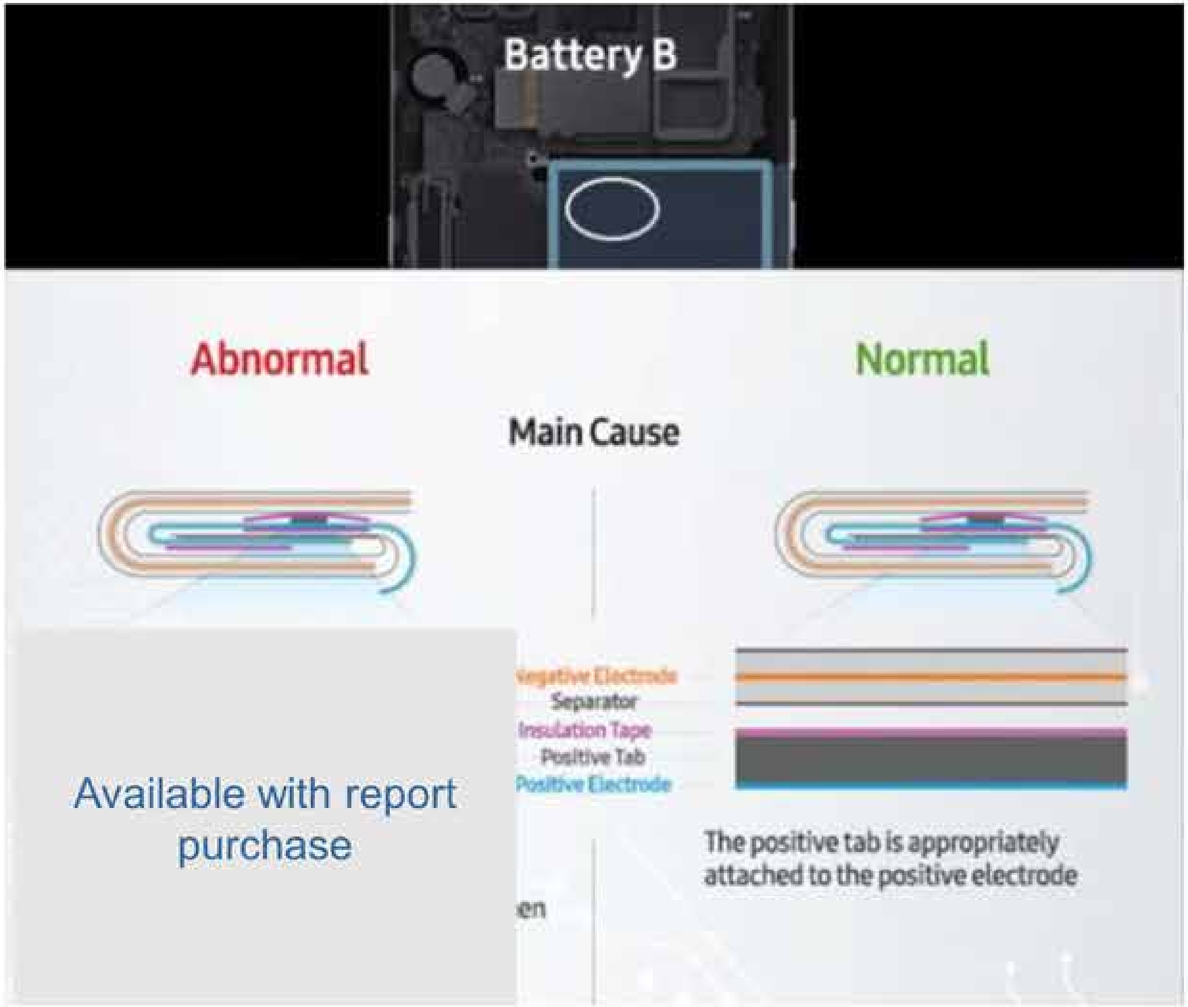

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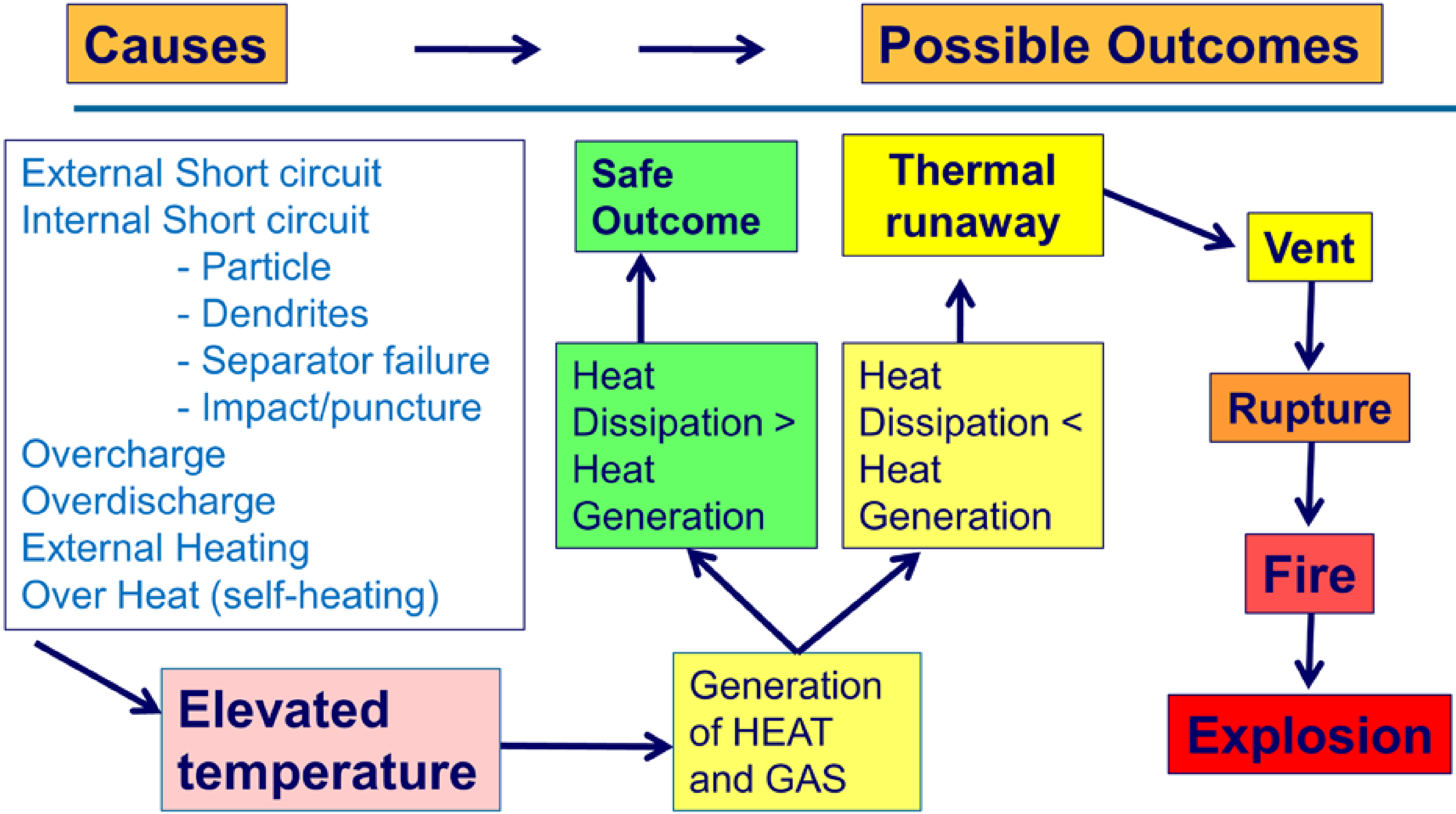
Causes
Possible Outcomes
External Short circuit
Internal Short circuit
- Particle
- Dendrites
- Separator failure
- Impact/puncture
Overcharge
Overdischarge
External Heating
Over Heat (self-heating)
Elevated temperature
Generation of HEAT and GAS
Heat Dissipation > Heat Generation
Safe Outcome
Heat Dissipation < Heat Generation
Thermal runaway
Vent
Rupture
Fire
Explosion

Description of Thermal Runaway

- The condition where battery cell is producing more internal heat than can be dissipated, leading to **uncontrolled self-heating** driven by chemical decomposition reactions.
- Thermal runaway occurs when internal cell temperature exceeds approximately 150°C (302°F).
    - Under normal electrochemical discharge, chemical energy is converted to electrical energy.
    - When chemical reaction predominates, chemical energy is converted to heat and gas.

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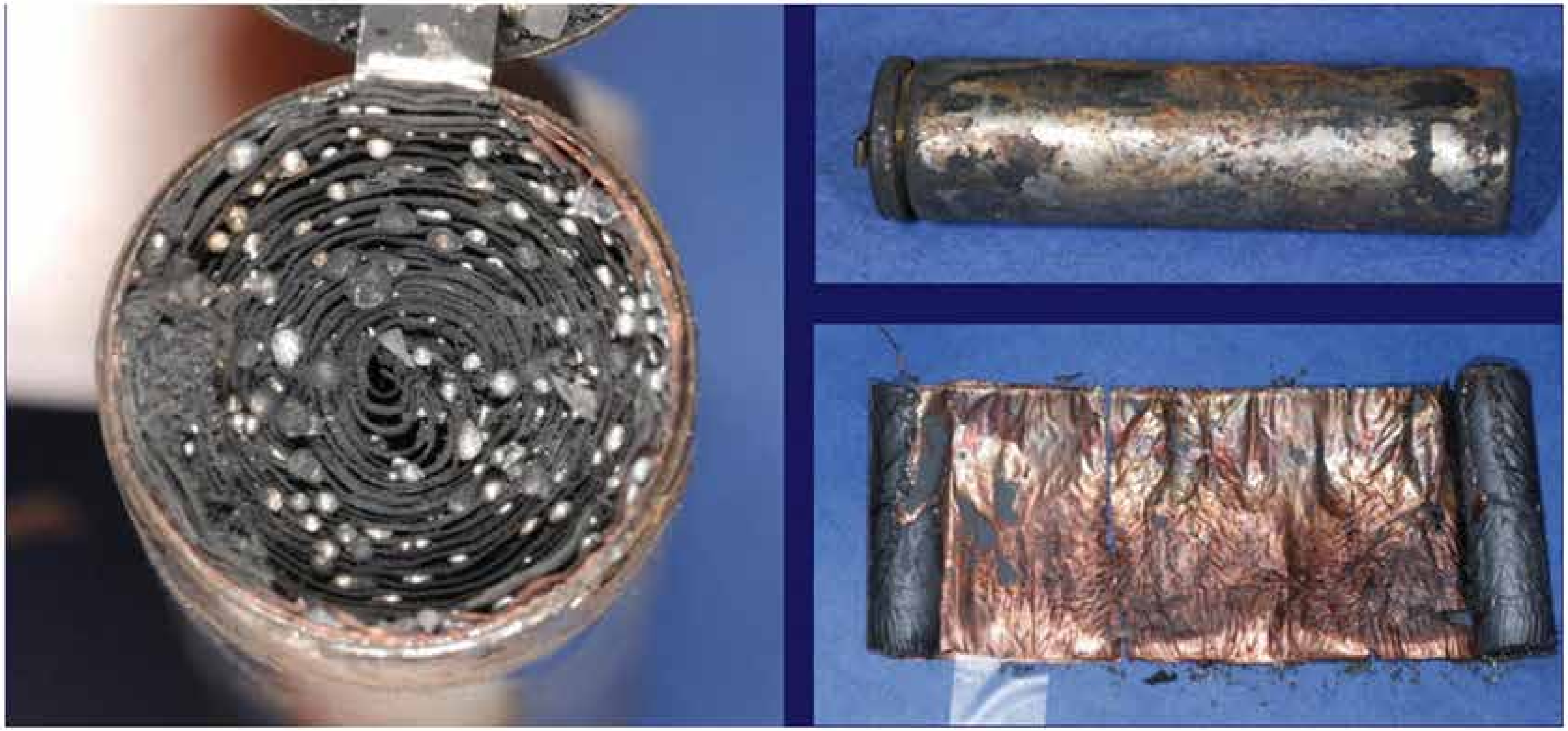
Maximum Temperature During Thermal Runaway Often Exceeds 660°C

- The beads of re-solidified aluminum (from cathode current collector) indicate the cell temperature must have exceeded 660°C (1220°F) – the melting point of aluminum.
- Copper melts at 1085°C (1984°F). The copper foil (anode current collector) did not melt.
- Therefore the internal temperature of the cell was between 660°C and 1085°C.



- **Types of Mechanical Abuse** that cause ***internal short circuit:***
  - Mechanical Shock
  - Vibration
  - Drop

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Cells With Internal Defects Often Fail during Charging

- Cell internal shorting failures are most likely to occur during or immediately after cell charging.*
  - Often, early cell cycling causes dimensional changes in cell components (e.g., volume expansion) and increased pressures within a cell case.
    - If a sharp contaminant or burr is present within a cell, dimensional changes or pressure increases may cause it to puncture separator layers and cause direct shorting.

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Do Li Dendrites Cause Thermal Runaway?

- **Typically you need to cycle 100s or 1000s of cycles beyond the first signs.**
  - Most dendrites likely would create benign "soft shorts".
  - A large, localized group of shorts could potentially heat up enough to initiate a thermal event.
  - But will the dendrite continue to carry the high current that is predicted to cause thermal runaway?
- **The likely prognosis**

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Definition of Severity – Automotive Example

Assign Hazard Severity Level Score

Hazard Level Adapted from EUCAR and SAND2005-3123

Severity Level	Description	Criteria for Severity Classification & Effects
0	No effect	No effect. No loss of functionality.
1	Reversible Loss of Function	No defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Temporary loss of battery functionality. Resetting of protective device needed.
2	Irreversible Defect/Damage	No leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. RESS irreversibly damaged. Repair needed.
3	Leakage Δ mass < 50%	No venting, fire, or flame*; no rupture; no explosion. Weight loss <50% of electrolyte weight. Light smoke (electrolyte = solvent + salt).
4	Venting Δ mass ≥ 50%	No fire or flame*; no rupture; no explosion. Weight loss ≥50% of electrolyte weight. Heavy smoke (electrolyte = solvent + salt)
5	Fire or Flame	No rupture; no explosion (*i.e.*, no flying parts).
6	Rupture	No explosion. RESS could disintegrate but slowly without flying parts of high thermal or kinetic energy
7	Explosion	Explosion (*i.e.*, disintegration of the RESS with externally damaging thermal & kinetic forces). Exposure to toxic substances in excess of OSHA limits

Note: SAE J2464 reverses Levels 5 and 6

Cyrus N. Ashtiani, USABC Li-Ion Battery Safety Update AABC 2008

- Examples of Safety Devices INSIDE the cell:
  - Burst Disk (Cell Vent) or Tear Away Tab
  - Current Interrupt Device (CID)

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- Examples of Safety Devices OUTSIDE the cell:

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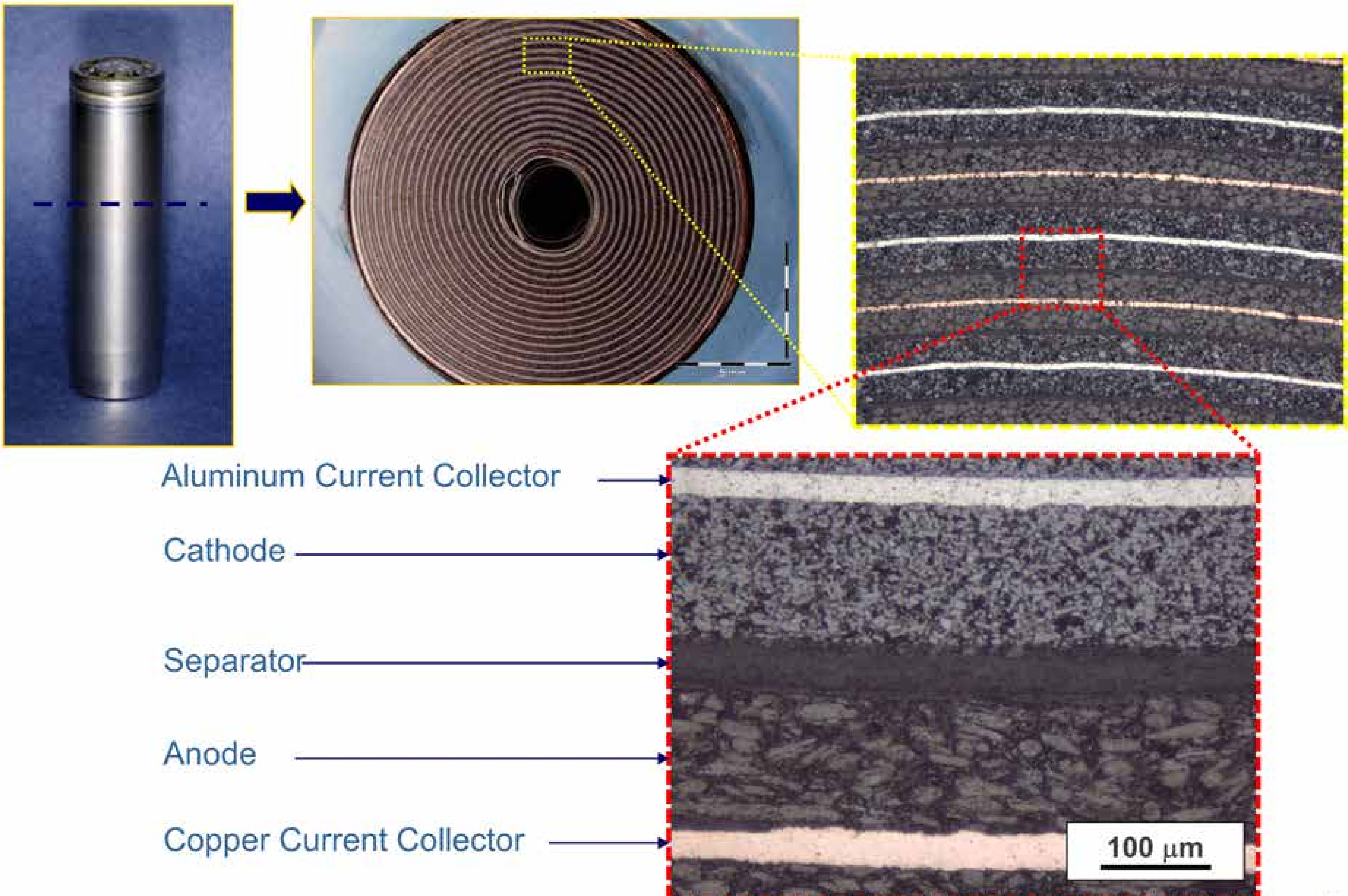
Cell Cross-Section



BMS Monitoring Functions

- A BMS may monitor the state of the battery as represented by various items, such as:
  - **Voltage**: total voltage, voltages of individual cells, minimum and maximum cell voltage, or voltage of periodic taps
  - **Temperature**: average temperature, coolant intake temperature, coolant output temperature, or temperatures of individual cells

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- The BMS will also control the recharging of the battery by redirecting the recovered energy (i.e.- from regenerative braking) back into the battery.

- A BMS may calculate values based on the above items, such as:
  - Maximum charge current as a charge current limit (CCL)
  - Maximum discharge current as a discharge current limit (DCL)
  - Energy [kWh] delivered since last charge or charge cycle

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BMS Safety Functions (1)

- A BMS may protect its battery by preventing it from operating outside its safe operating area, such as:

- Over-current (may be different in charging and discharging modes)
- Over-voltage (during charging)

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- Ground fault or leakage current detection (system monitoring that the high voltage battery is electrically disconnected from any conductive object touchable to use such as vehicle body)

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  - 3 Case Studies: Chevy Volt, Tesla, Boeing 787
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Cell Failures have Been Observed in Many Situations

Transportation

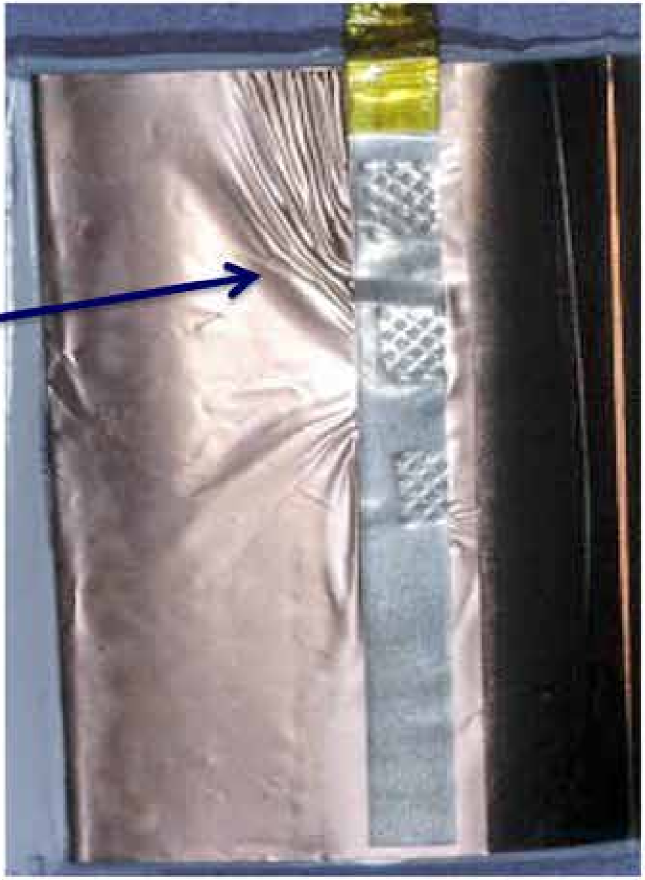
Consumer Electronics

Aviation

787 Dreamliner Battery Fires
http://www.nytimes.com/2013/01/17/business/faa-orders-grounding-of-us-operated-boeing-787s.html?hp&_r=0

Spontaneous Internal Short (1)

- Caused by mechanical flaws in the cell
  - Included particles
  - Sharp edges, burrs
  - Folded corners
  - Wrinkled electrodes
  - Improper tab folding/bending
  - Core collapse
- No fix at the system level
- Requires cell design and process controls



Different Short Circuit Current Paths Have Different Resistance

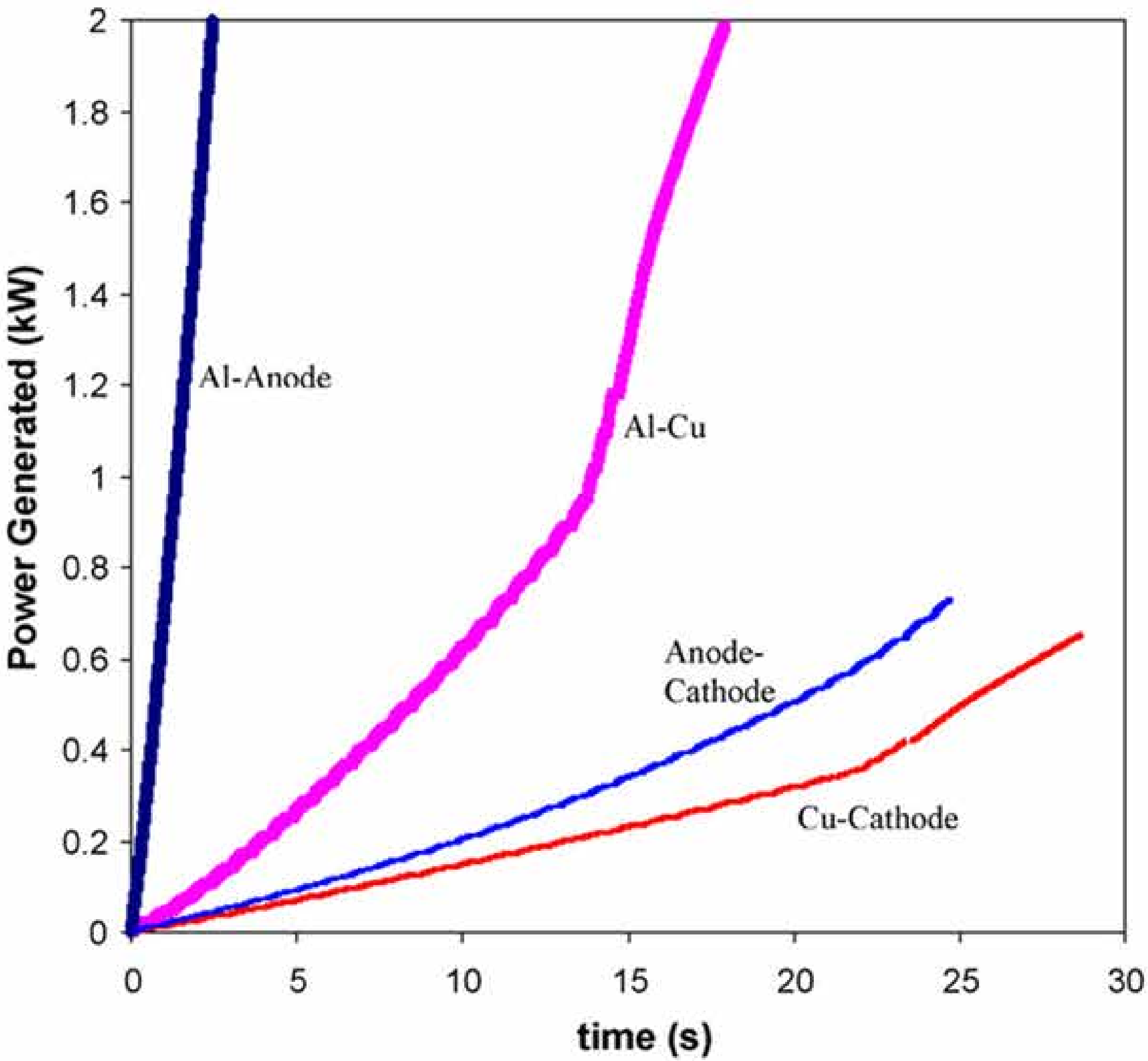
Power generated after various types of short-circuit scenarios in a lithium-ion cell:

Type 1, short occurs between active materials at the cathode and anode.

Type 2, short occurs between aluminum and the anode material.

Type 3, short occurs between copper current collector and the cathode active material.

Type 4, short occurs between the two current collectors (Al-Cu).

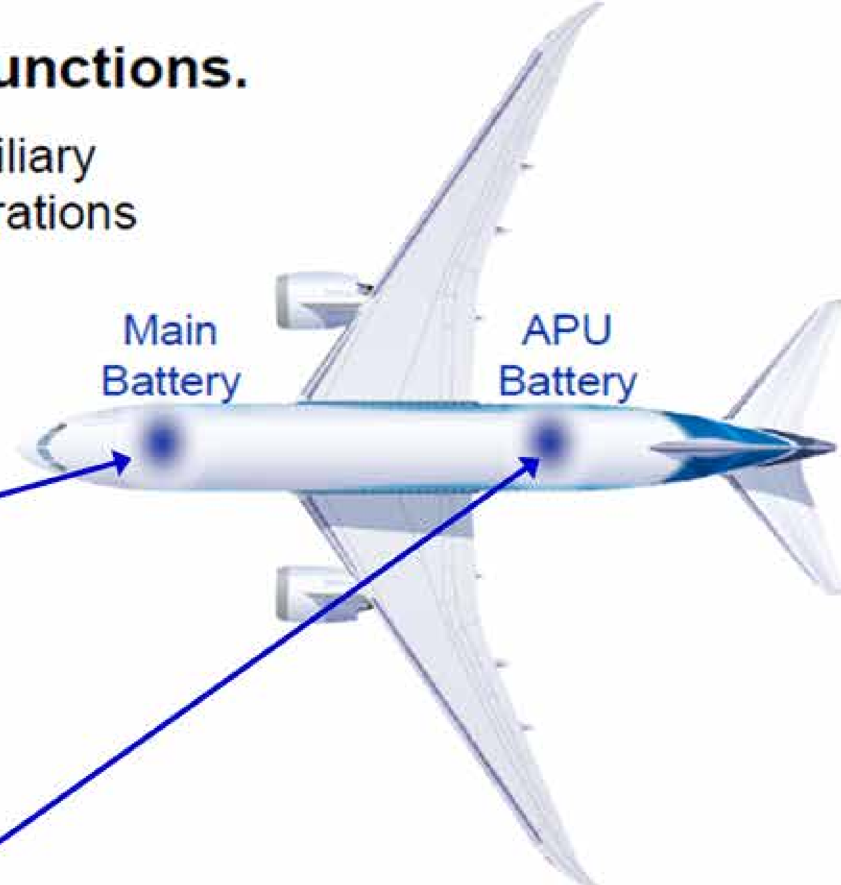


Case Study #2 – Tesla Battery Fires

- **On October 1, 2013 a Model S caught fire after the vehicle hit metal debris on a highway in Kent, Washington.**
- **Caused by the "direct impact of a large metallic object to one of the 16 modules within the Model S battery pack".**
  - Note that ~440 cells (18650-size) in 1 module.
  - Probably several cells got shorted from the impact.
- **The fire in the battery pack was contained to a small section in the front of the vehicle.**

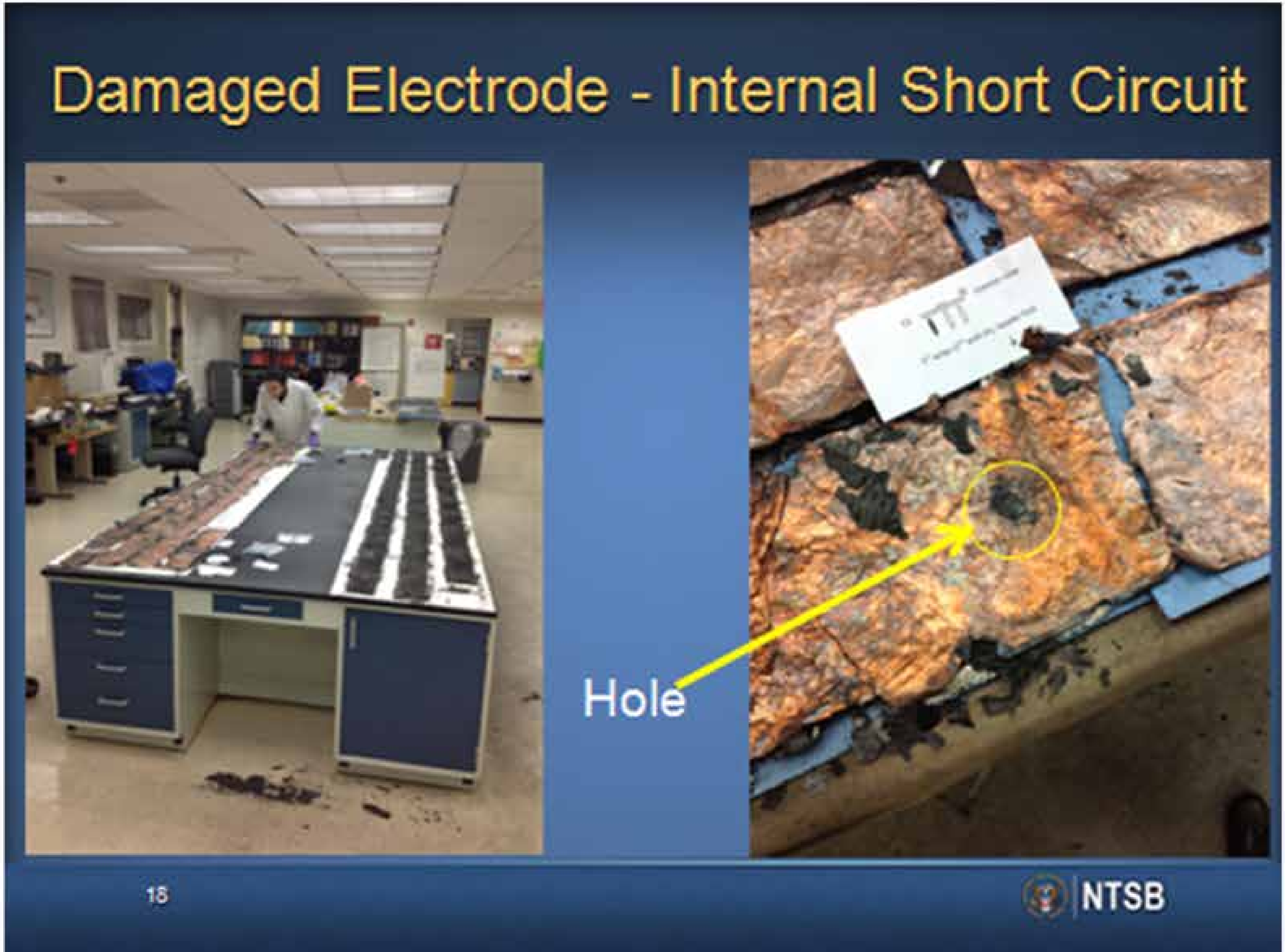
Boeing 787 Overview – Main and APU Batteries

- **Batteries perform limited functions.**
  - Primary function: on-ground auxiliary power unit start and ground operations
  - Secondary function: in flight, one of multiple sources of backup power

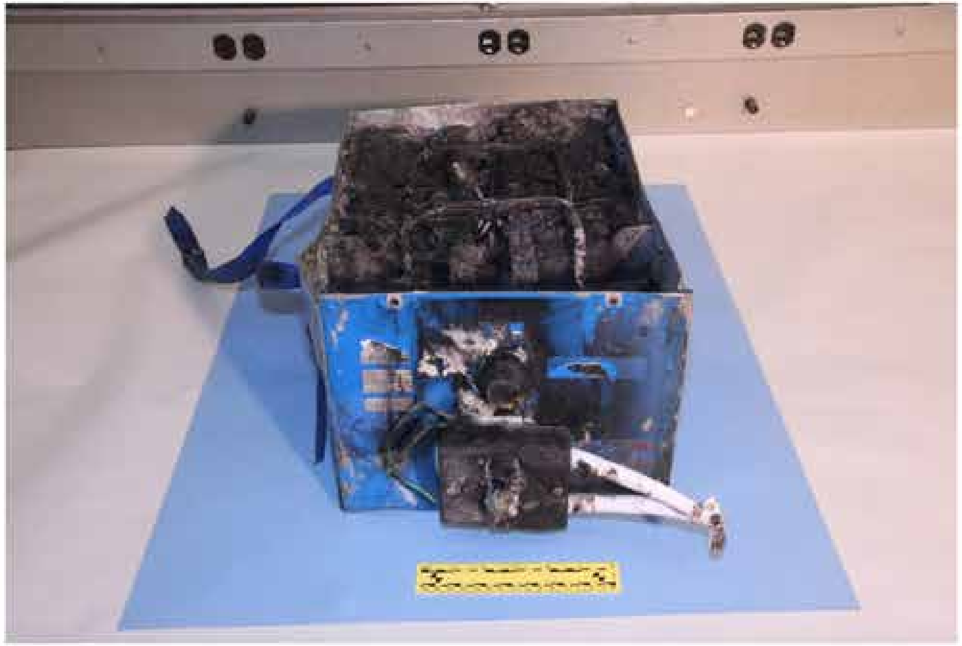


Batteries Not Needed for Safe Flight or Landing

Slide Courtesy of Tomas P. Barrera.
Ref: Boeing 787 Battery Investigative Hearing – Presentations, 4/23/2013. http://www.ntsb.gov/


Damaged Electrode - Internal Short Circuit
Hole
18
NTSB

The exotherm aboard JAL (Logan Airport ,Boston, USA) was more intense than the event aboard ANA (Takamatsu, Japan).



JAL battery (Boston, USA)

ANA battery (Takamatsu, Japan)

However, the cell failures propagated and
all cells were consumed **in both events.**

Probable Cause:

- Internal short circuit within a cell of the auxiliary power unit (APU) lithium-ion battery, which led to thermal runaway that cascaded to adjacent cells, resulting in the release of smoke and fire.

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Additional Corrective Actions

- **System Level**
  - *Battery containment and over-board venting capability*
  - Decrease BMU/BCU voltage regulation level from 32.2 to 31.9Vdc
- **Battery Level**
  - *Multiple battery design changes to mitigate cell-to-cell propagation*
  - Increase over-discharge contactor latch limit in the BMU from 1.7 to 2.4Vdc
  - Enhanced ATP to determine performance during high-load duty cycles
- **Cell Level**
  - *No cell-level design changes*
  - Enhanced ATP to screen for soft shorts
  - Manufacturing improvements (such as FOD and cleanliness controls)
- **Additional cell failure on Jan. 14, 2015 at Narita Airport, Tokyo**
  - Flight was on the ground – vent gas was vented overboard.
  - One cell vented – No propagation.

Slide Courtesy of Tomas P. Barrera.

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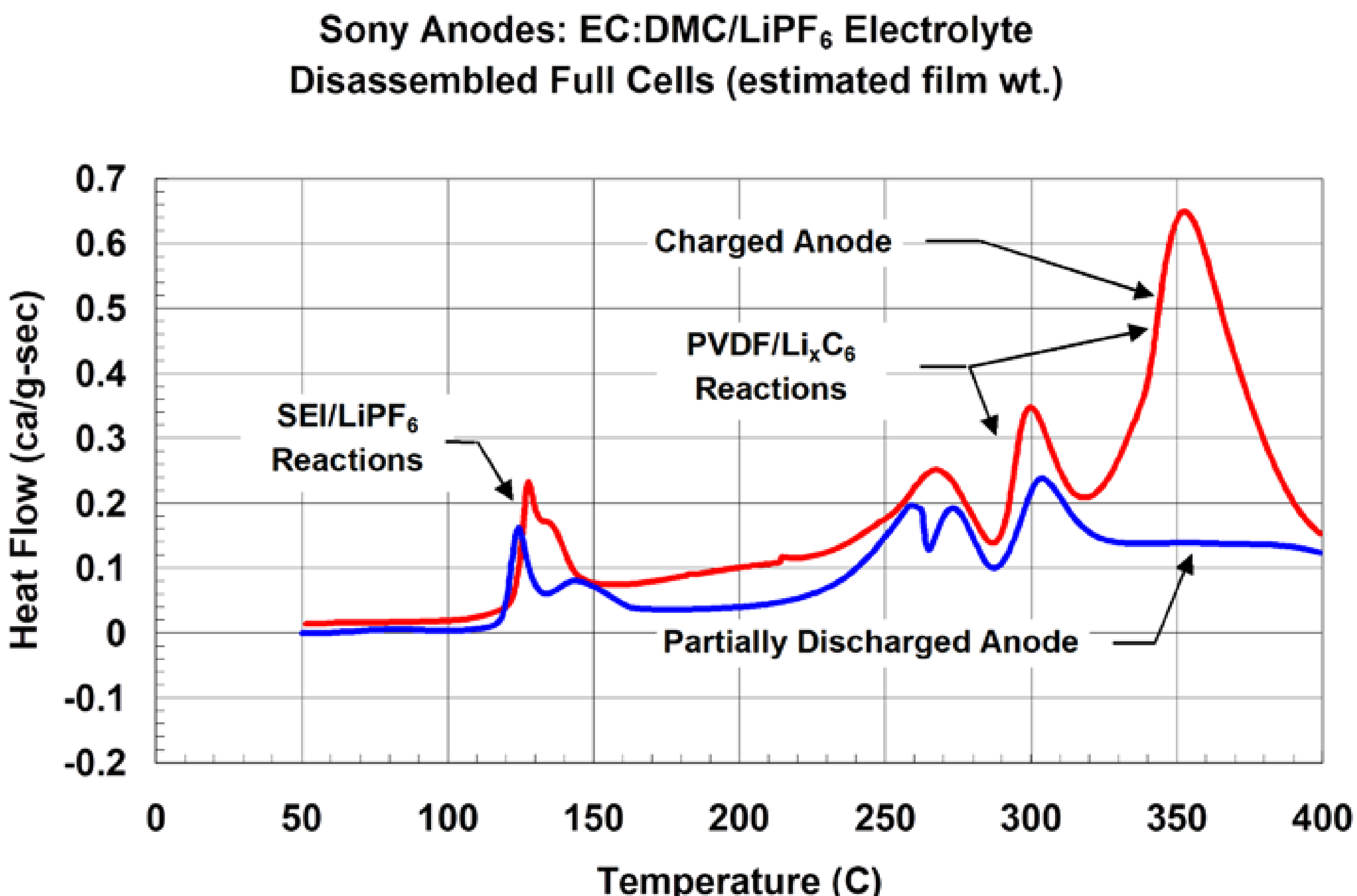
Differential Scanning Calorimetry (DSC)

- Measure material thermal reactions at constant heating rate
- Determine reaction enthalpies and activation energies

Example:
DSC runs of Sony anodes charged & discharged in electrolyte*

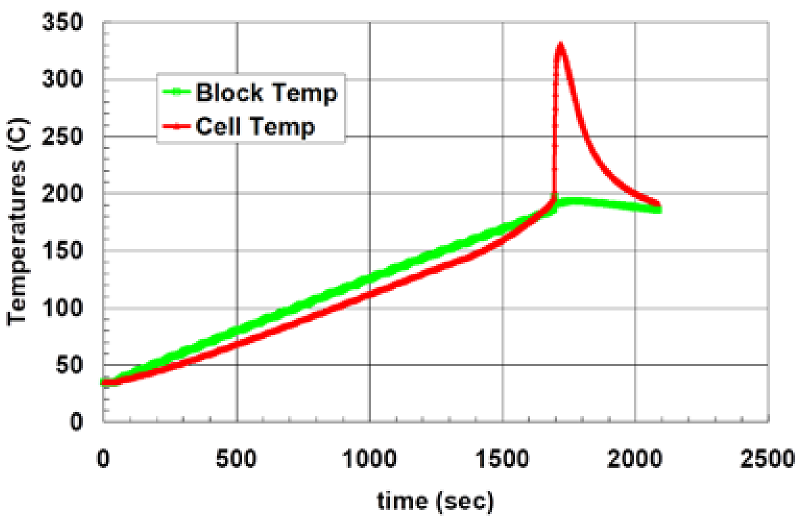
*SANDIA REPORT SAND2004-0584 March 2004, "*Thermal Abuse Performance of 18650 Li-Ion Cells*", E. Peter Roth, Chris C. Crafts, and Daniel H. Doughty



Three regimes:

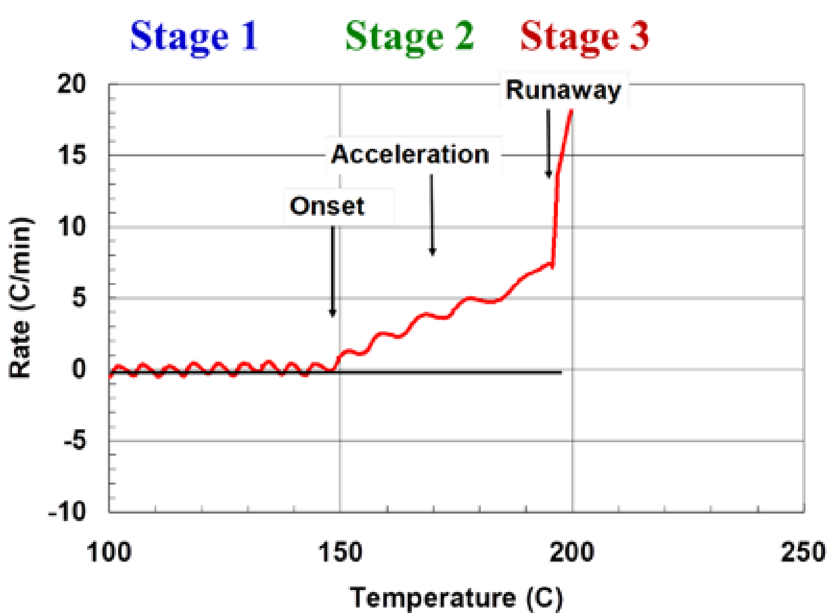
- **Stage 1: < 160°C – Onset** (SEI layer breakdown, electrolyte degradation, etc.)
- **Stage 2: 160°C - 190°C – Acceleration** (cell vent, accelerated anode and electrolyte degradation, onset of cathode decomposition)
- **Stage 3: > 190°C – Runaway** (full cell materials degradation, energetic release and uncontrolled rapid disassembly)

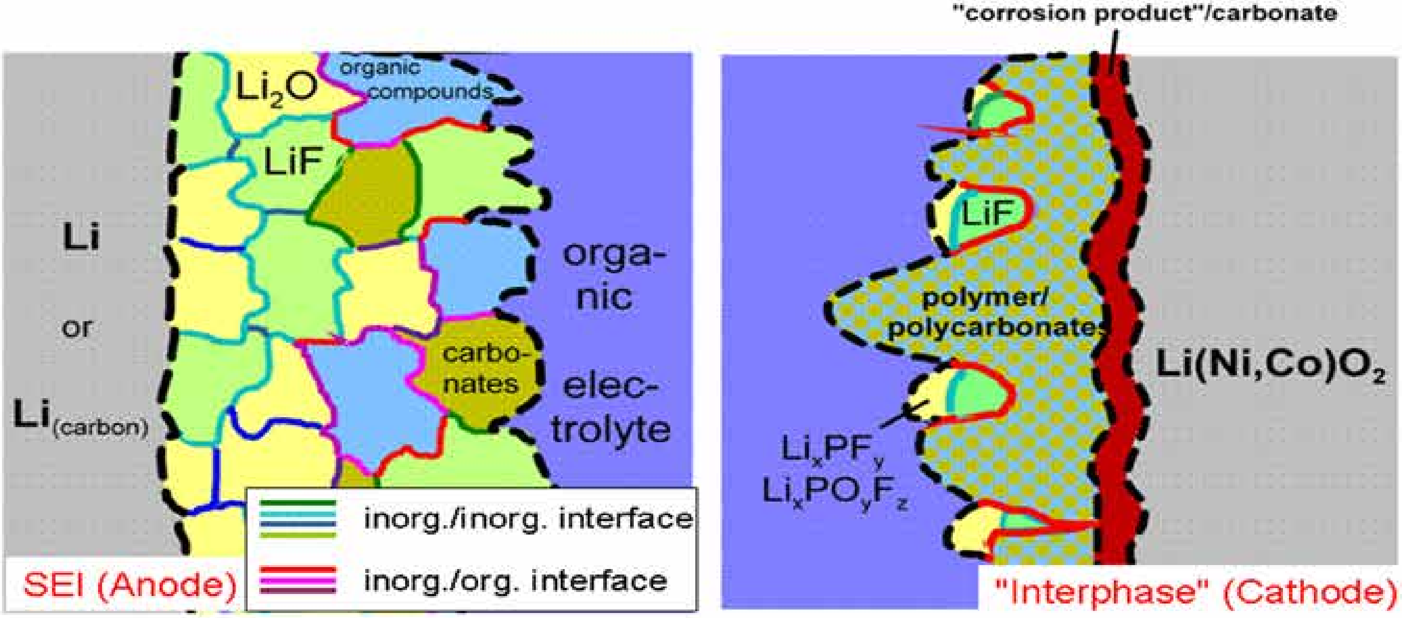
Ramp Temperatures



Thermal Ramp Response (100% SOC)

Differential Temperature Rate





Courtesy of Prof. Martin Winter of Muenster University

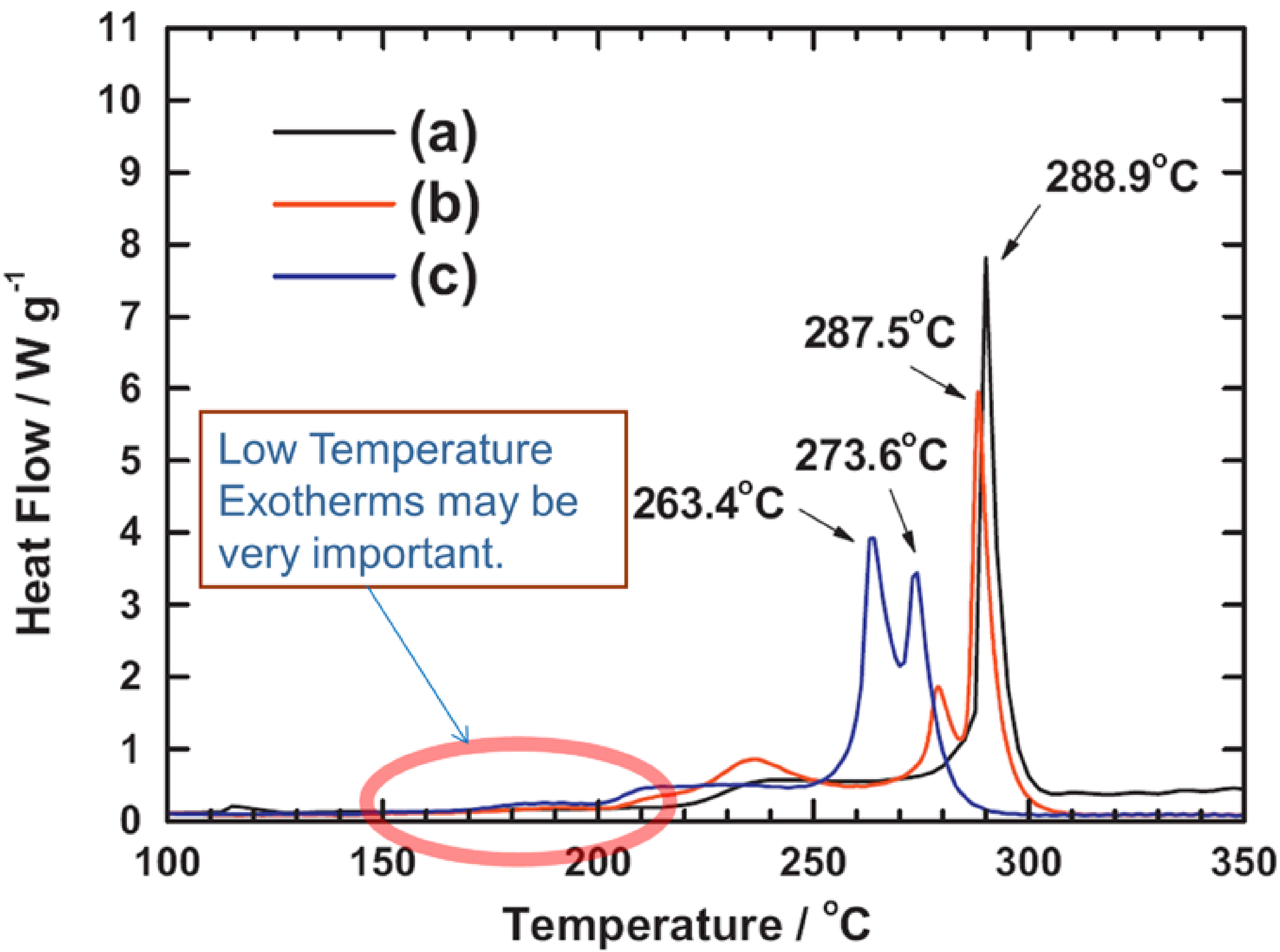
SEI/Interphase Composition:

- is different on anode and cathode and complex (many reports, often contradictory)
- depends on electrolyte and electrode (surface) chemistry and morphology
- depends on applied electrochemical & thermal conditions during SEI formation

Interphases affect life and safety!

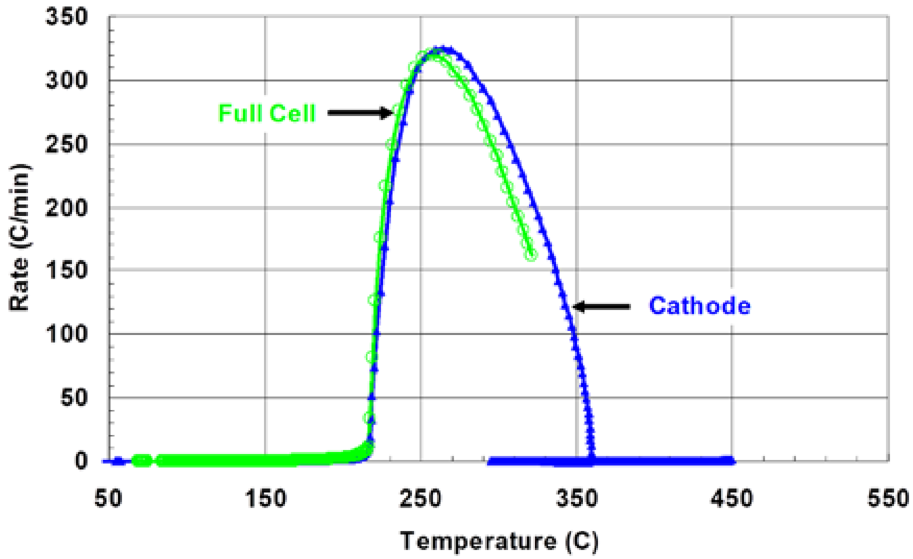
Small DSC Peaks Below 200°C

DSC of three types of cathode with electrolyte

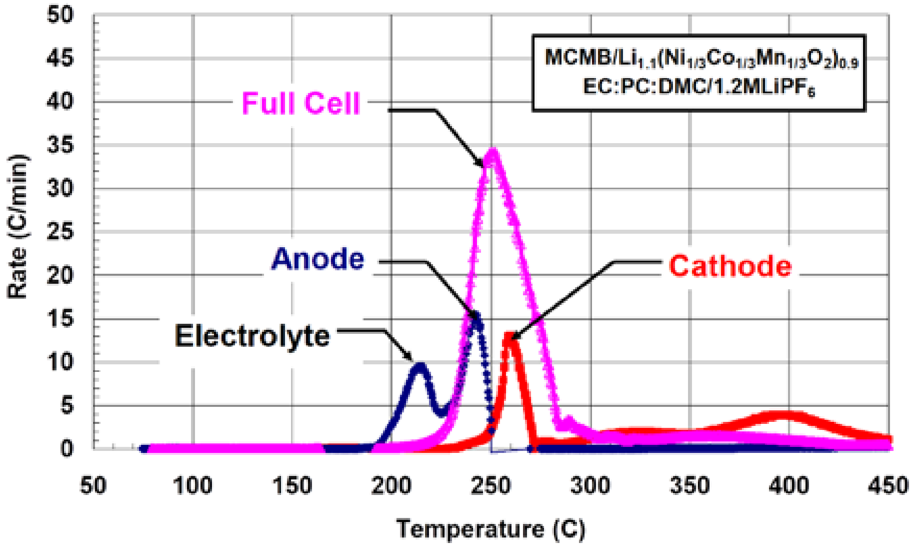


Peak thermal runaway profile determined by cathode reactions

$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$



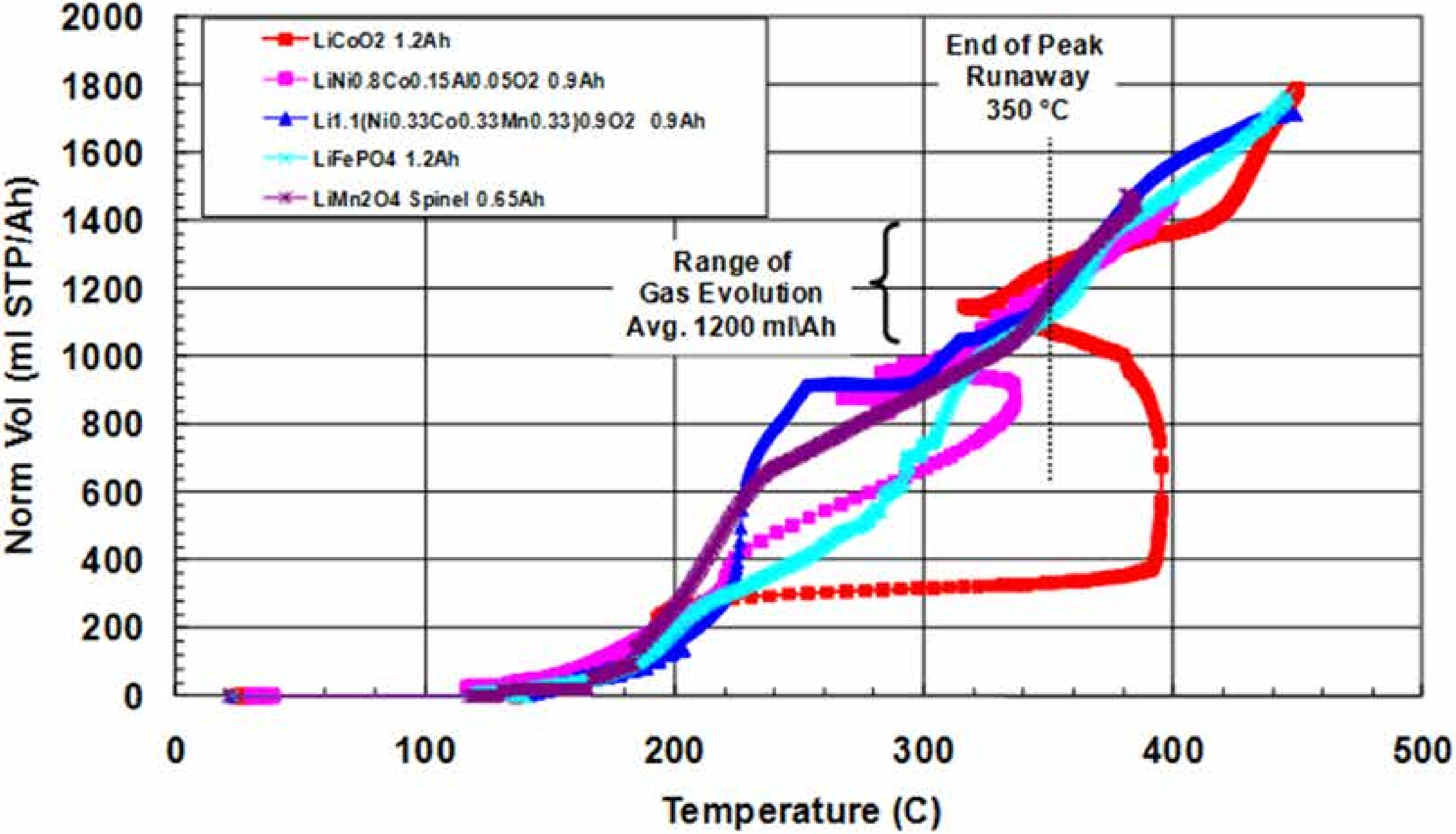
$Li_{1.1}(Ni_{1/3}Co_{1/3}Mn_{1/3})_{0.9}O_2$



Comparison of cathode and anode removed from full cell at 100%SOC (resealed in 18650 cans with electrolyte) with full cell data

Gas evolution is independent of cathode composition and correlated to Ah capacity of cell

~ 5ml electrolyte in 1.2Ah 18650 cell yields ~ 1.2L(STP)/Ah at peak, 1.5-2.0L/Ah total
(Various Electrolytes)



➢ SEI Enhancing Additives to Improve Anode Thermal Stability

Believed to form polymerized coating on anode surface

- Vinylene Carbonate (VC)
- Vinyl Ethylene Carbonate (VEC)
- Oxalato group additives (e.g. LiBOB)

➢ Flame Retardants

Two mechanisms have been suggested to explain the flame retardation:

- A physical char-forming process, which builds up an isolating layer between the condensed and gas phases to retard the combustion process, and
- A chemical radical-scavenging process, which terminates the radical chain reactions responsible for the combustion reaction in the gas phase.

- Flame reactions for combustible liquids (and also for solids) always occur in the gas or vapor phase.
- The combustion is only sustained when it releases more heat than what is absorbed by the surrounding environment.
- The thermal energy which is produced by the combustion converts a part of the fuel to vapor (or decomposes a part of the solid) to form a combustible gas phase mixture which keeps the combustion process alive.

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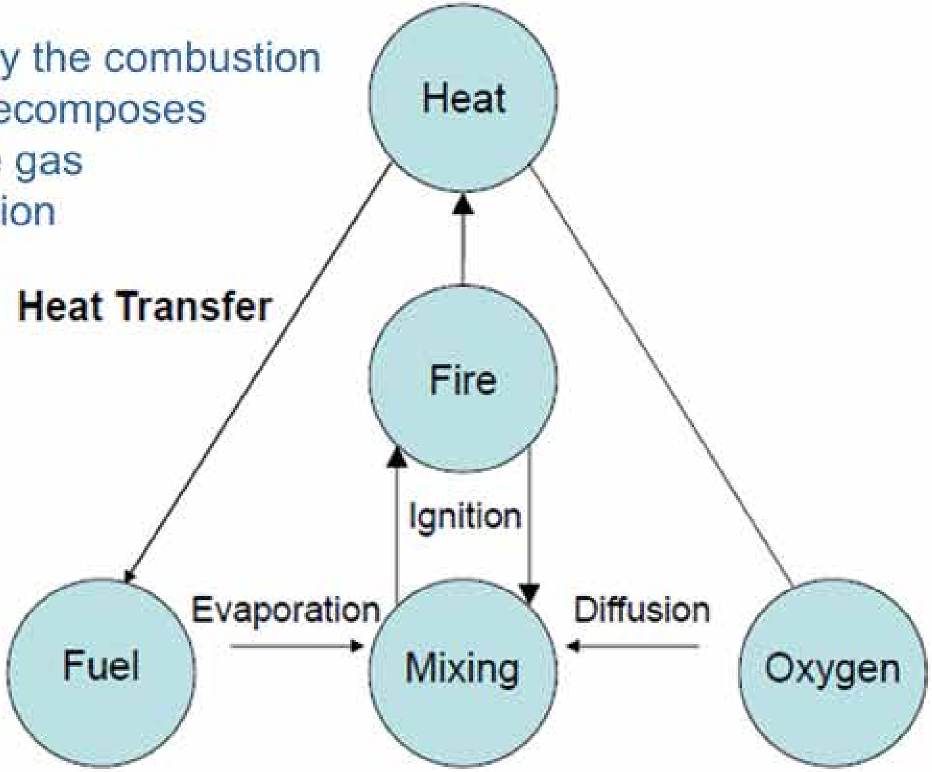

Flame Retardant Issues

- Additives, at levels that do not affect performance, do not necessarily result in a non-flammable electrolyte
- Some additives are not stable with common cathode materials

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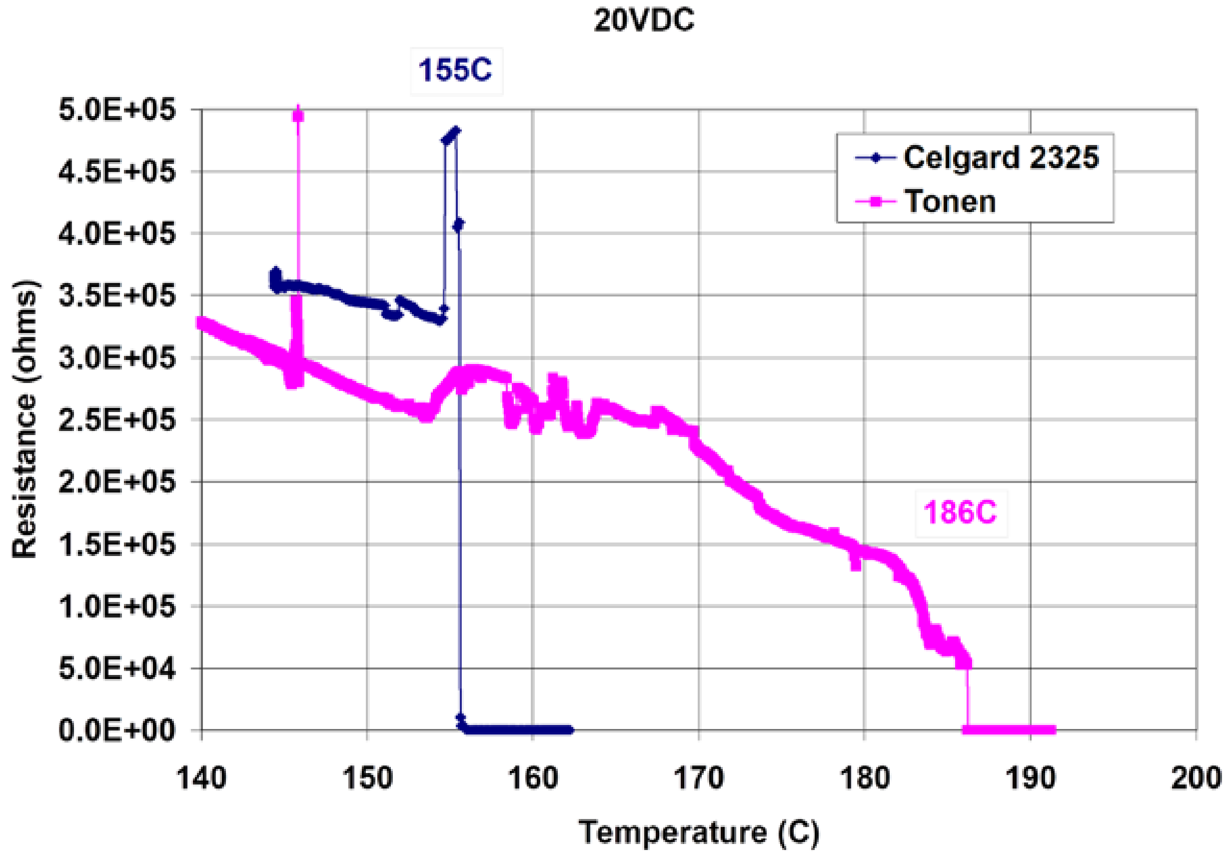
- Added cost

DC Resistance Above Shutdown

Local currents through pinhole defects above shutdown result in local heating and further separator failure leading to shorting of electrodes



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Types of Abuse Tolerance Tests

Abuse scenarios can involve more than one abuse condition.

Electrical Abuse Tests

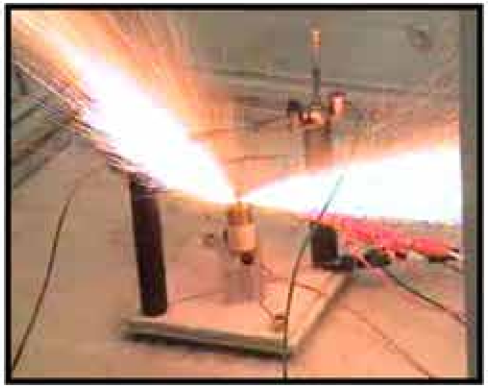
- Overcharge
- Overdischarge
- External short circuit
- Internal short circuit

Thermal Abuse Tests

- Thermal stability (discussed in previous slides)
- High temperature (simulated fire)
- Cycling without thermal management
- Thermal shock cycling
- Propagation resistance

Mechanical Abuse Tests

- Crush
- Shock
- Vibration
- Drop
- Immersion
- Nail penetration



Sources of Electrical Short Circuits

External Short Circuit

- Resulting from accident event (most common type of abuse)
- Resulting from mishandling during assembly or maintenance
- Resulting from other failure event (e.g., ejecta from another call in thermal runaway creates conductive path)
- Often, higher severity may be seen in abuse response for intermediate resistance shorts compared to hard shorts

Internal Short Circuit

- Often resulting from manufacturing defect (foreign particles, displaced leads, loose connection, faulty BMS, etc.)
- Unpredictable and can results in catastrophic failure
- Very rare occurrence (estimated at 1 in 5 to 10 million cells)

Internal Short-Circuit Tests – Status

- Sometimes called "Internal Fire" or "Forced Internal Short-circuit Test"
- Several organizations are trying to develop internal short-circuit tests:
  - UL & NASA (Blunt Nail Crush)
  - Motorola & ORNL (Pinch Test with 2 large spheres)
  - Japanese Industrial Standard (JIS) (insertion of "L-shaped" metal into cell between electrodes)

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ISC Device Strengths and Weaknesses

- Strengths of ISC Device Method
  - Minimizes heating of adjacent cells
  - Minimizes modification of battery pack (no insertion of heater)

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- Weaknesses of ISC Device Method
  - Requires a willing cell manufacturer to do the implantations
  - Reliability has not been established

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Prognosis on Internal Short-Circuit Tests in Development

- Test is useful in measuring progress in development of cells with better abuse tolerance
  - Cell manufacturer should perform internal short-circuit test to guide changes to reduce severity of response
- Challenges need to be overcome before it is suitable for safety & abuse test standards
  - Must be relevant to production cells

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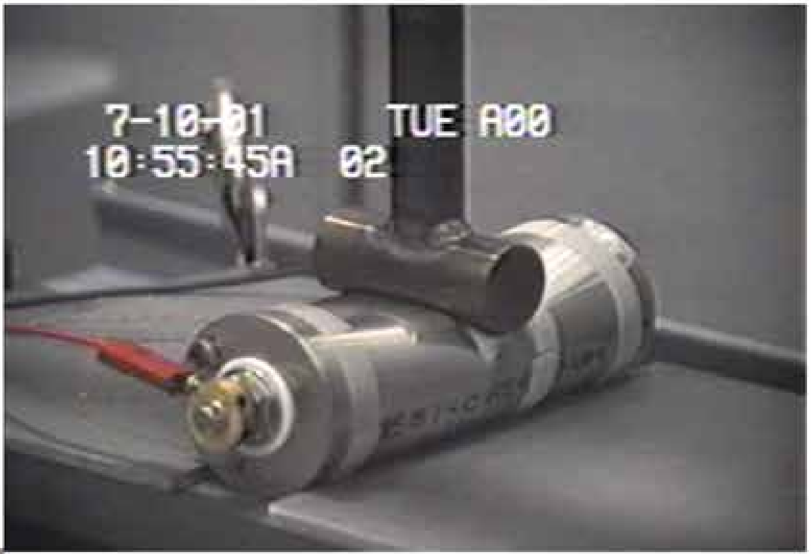
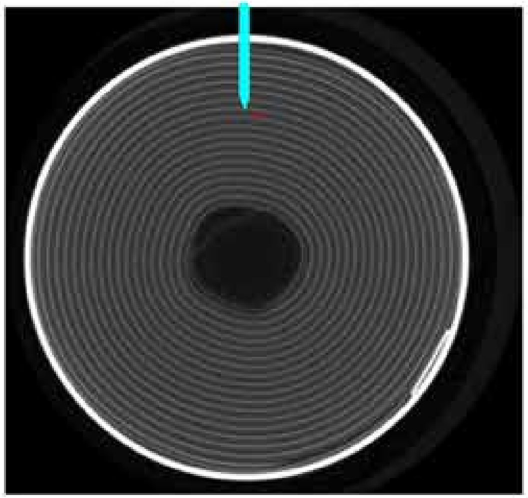
Mechanical Abuse Tests

- Crush
- Shock
- Vibration
- Drop
- Immersion
- Nail Penetration



Nail Penetration Test (2)

- Nail will short the cell … across many electrode pairs!
- R_s will vary wildly
  - From layer to layer
  - From test to test
- Every detail matters
  - Nail size
  - Tip shape
  - Nail speed
  - Nail temperature
  - Nail surface
  - Nail E&T isolated?
- Very different from spontaneous internal short



Section 2.

Understanding Battery Failure Modes

- Understanding Battery Failures
  - General
  - 3 Case Studies: Chevy Volt, Tesla, Boeing 787
- Li-Ion Battery Safety & Abuse Characterization Tests
  - Thermal Runaway Analysis Techniques
  - Abuse Response of Cell Materials
    - Anode (Negative Electrode)
    - Cathode (Positive Electrode)
    - Electrolyte
    - Separator
  - Test Standards that Evaluate the Abuse Response of Cells and Batteries
    - General Considerations
    - Electrical Abuse Tests
    - Thermal Abuse Tests
    - Mechanical Abuse Tests
- Propagation of Thermal Runaway of Single Cell
- Abuse Tolerance Simulation
- Effect of Cell and Pack Design on Abuse Response

Thermal Runaway Trigger Methods: Which is best for battery testing?

Conventional Methods

- Mechanical – Crush or nail penetration
  - Compromises cell and battery enclosures
  - Difficult to do to interior cells in a pack
- Electrical – Overcharge
  - Triggers at too high states of charge, with generally more violent output than ISC
  - Requires cell to be electrically isolated from parallel cells in pack
- Thermal – Over-temperature exposure
  - Requires low-profile custom high-flux heaters
  - May interfere with cell-to-heat sink interface
  - Some risk for biasing adjacent cells
  - Weakens strength of cell can prior to thermal runaway
  - Often the best or most practical choice

Implantable device to trigger an ISC

- Implantation of nickel "L-shape" inside jellyroll (BAJ-FIST, TIAX) of fully charged cells
  - Operationally hazardous to perform
  - The only battery design/test accommodation required is heating cell to the point of melting alloy
- NREL/NASA implantable ISC device or SNL implantable low-melting metal alloy particle.
  - Negligible impact on cell performance
  - The only battery design/test accommodation required is heating cell to the point of melting wax or low-melting alloy,
  - Main downside – Requires a willing cell manufacturer to do the implantations

Design Priorities for Reducing Hazard Severity from Failure of a Single Cell

- Provide adequate cell spacing
  - Direct contact between cells without alternate heat dissipation paths nearly assures propagation.
- Individually fuse parallel cells
  - Cell in thermal runaway becomes an external short to adjacent parallel cells and heats them up.
- Reduce risk of cell-can side-wall ruptures

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Thermal Runaway Trigger Methods – Which is best for battery testing?

Conventional Methods

- **Mechanical** – Crush or nail penetration
  - Compromises cell and battery enclosures
  - Difficult to do to interior cells in a pack
- **Electrical** – Overcharge
  - Triggers at too high states of charge, with generally more violent output than ISC
  - Requires cell to be electrically isolated from parallel cells in pack
- **Thermal** – Over-temperature exposure
  - Requires low-profile custom high-flux heaters
  - May interfere with cell-to-heat sink interface
  - Some risk for biasing adjacent cells
  - Weakens strength of cell can prior to thermal runaway
  - Often the best or most practical choice

Implantable device to trigger an ISC

- Metallic implantation inside jellyroll (BAJ-FIST, TIAX) done on fully charged cells
  - operationally hazardous to perform
  - Only battery design/test accommodation required is heating cell to melting point of alloy
- NREL/NASA implantable ISC device or SNL implantable low melting metal alloy particle.
  - Negligible cell performance impact
  - Only battery design/test accommodation required is heating cell to melting point of wax or low melting alloy
  - Main downside – Requires a willing cell manufacturer to do the implantations.

Separator choice

- Shutdown or non-shutdown?
  - High-voltage series strings may result in breakdown
- Inorganic particle coatings and additives
  - May protect against some internal shorting conditions
  - Not effective during thermal excursions

Internal safety devices

- Positive Temperature Coefficient (PTC) device
  - May breakdown in high-voltage series strings and become a source of heat generation
  - Not compatible with some high-power applications
- Current Interrupt Device (CID)
  - Requires pressure generation but holds up well to high voltage
- Burst disc
  - Prevents high pressure buildup
- Internal fuse
  - Only practical for certain cell geometries (i.e., difficult to incorporate in pouch cells)

Pack Design Choices Affecting Safety (1)

Many layers of system controls and safety mechanisms are required to assure redundancy. A single point of failure cannot be allowed to result in a propagating, cascade failure of the whole pack.

- **Power/Energy Capacity**
  - Dangers associated with high voltages
  - High capacity (kWh) means more cells with greater stored electrochemical energy
  - Choice of high specific energy cells (more is not better from the safety perspective)
  - A greater number of cell interconnects allows for a greater chance of failure
- **Battery Management System Control Level (cell level/module level)**

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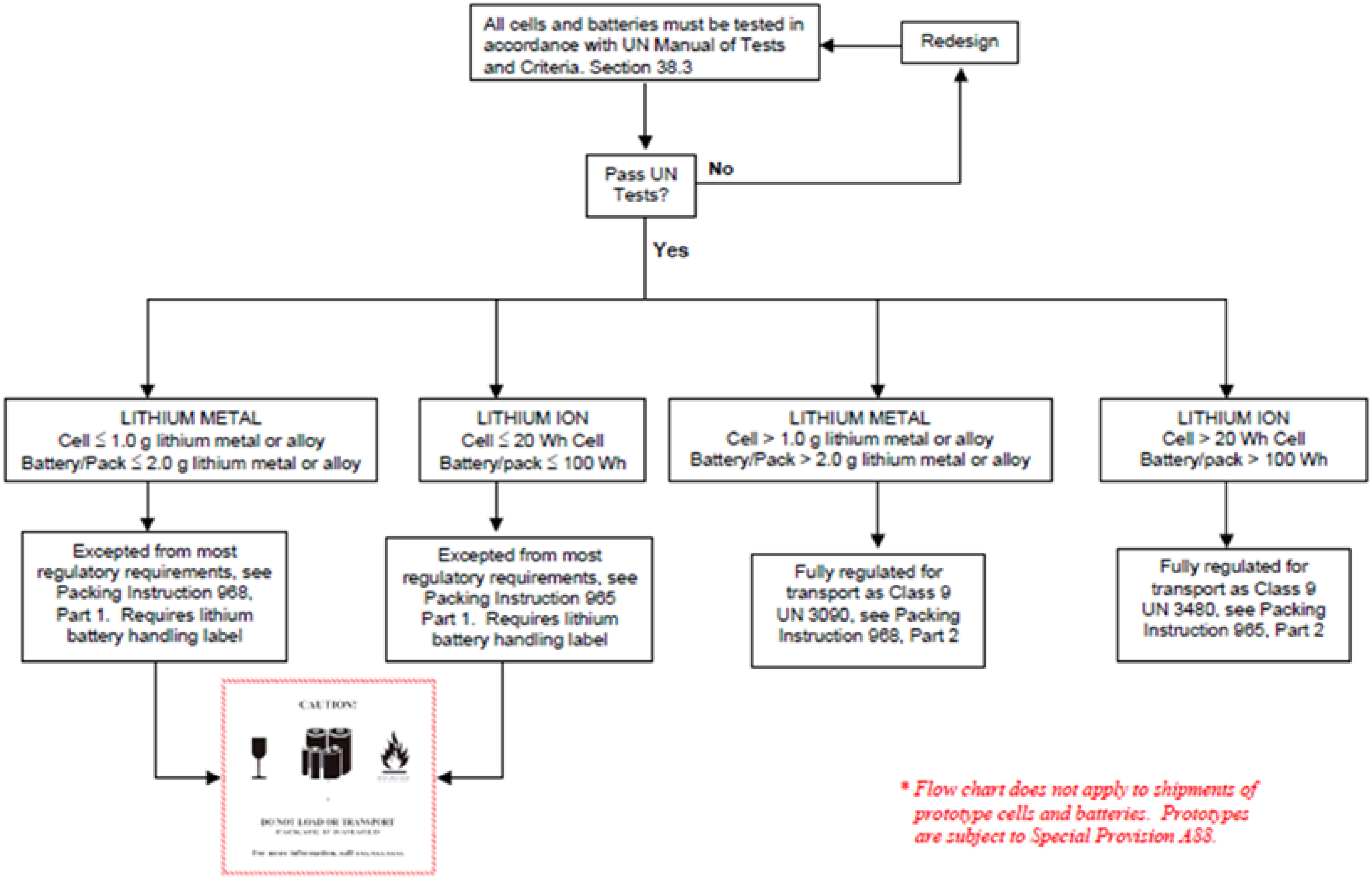
- **Section 1. Background and Fundamentals of Battery Safety**
  - Battery Safety Fundamentals
  - Examples of Recent Recalls
  - Hazards & Thermal Runaway
  - Cell Failures
  - Safety Devices
- **Section 2. Understanding Battery Failure Modes**
  - Understanding Battery Failures
  - Li-Ion Battery Safety & Abuse Characterization Tests
  - Propagation of Thermal Runaway of Single Cell
  - Abuse Tolerance Simulation
  - Effect of Cell and Pack Design on Abuse Response
- **Section 3. Safety Validation: Abuse Testing Methods & Procedures**
  - General
  - Shipping Procedures
  - Pass/Fail vs. Safety Characterization Tests
  - Test Procedure Comparisons
  - Functional Safety
  - What's Missing?
- **Summary and Conclusions**
- **Appendix: Organizations that Publish Safety Test Standards**

Organizations that Publish Safety Test Standards

- **There are at least 18 organizations that publish battery safety test standards.**
  - Each organization can publish multiple standards.
  - Governmental Regulatory Agencies have requirements that have legal standing.
  - Trade Organizations provide guidance that may be incorporated into regulations.
    - A list and information on Organizations that Publish Safety Test Standards is provided in the Appendix.

LITHIUM ION AND LITHIUM METAL CELLS AND BATTERIES SHIPPING REQUIREMENTS *



** Flow chart does not apply to shipments of prototype cells and batteries. Prototypes are subject to Special Provision A88.*

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Comparison Table #2 – Mechanical Abuse Tests

Test Title	Cell & Pack	Cell & Pack Testing / Automotive Applications						
	UN Section 38 Shipping	SAE J2464 2009 HEV and EV Battery Abuse Tests	SAE J2929 EV and HEV Battery Safety Standard - Li Cells	IEC 62660-2 Li cells for EVs– Part 2: abuse testing	ISO/CD 12405 Electrically propelled road vehicles	UL 2580 "Batteries for Use in Electric Vehicles"	Korea MVSS 18-3 "Driving Battery Safety Test"	India AIS-048 Battery Operated Veh. - Safety Requirements
Altitude	X							
Vibration	X		X	X	X	X		x
Drop Test		X	X			X	X	
Mechanical Shock	X	X	X	X	X	X		x
Impact	X							
Crush		X	X	X		X		
Nail Penetration		X						x
Roll-Over		X				X		x
Immersion		X	X			X	X	
Humidity Exposure (Dewing)			X		X			

- Greater variety of tests.
- None of the tests have universal acceptance.
- The tests are Often done differently.

- Section 1. Background and Fundamentals of Battery Safety
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What is the current status of battery safety?

- Safety is improving
- The biggest ***materials*** problems are:
  - **Electrolyte flammability & gas generation**
  - Oxidative nature of cathode
  - SEI instability
  - Poor separator integrity
- The biggest ***systems*** problems are:
  - **Propagation of failures from cell to cell**
  - Vulnerability to internal short circuit
  - Poorly-controlled manufacturing processes

List and Information on Organizations that Publish Safety Test Standards

1. American Institute of Aeronautics and Astronautics (AIAA)
2. American National Standards Institute (ANSI)
3. Battery Safety Organization (BATSO)
4. China (PRC)
5. Automotive Research Association of India (ARAI)
6. European Council for Automotive R&D
7. International Air Transport Association (IATA)
8. International Electrotechnical Commission (IEC)
9. International Civil Aviation Organization (ICAO)
10. Institute of Electrical and Electronics Engineers (IEEE)
11. International Organization for Standardization (ISO)
12. Japan Automobile Research Institute (JARI)
13. Japanese Industrial Standards (JIS) Committee
14. Korean Motor Vehicle Safety Standard
15. National Aeronautics and Space Administration (NASA)
16. National Electrical Manufacturer's Association (NEMA)
17. Society of Automotive Engineers (SAE)
18. Underwriters Laboratories, Inc. (UL)
19. United Nations (UN)
20. U.S. Department of Transportation (DOT) – National Highway Traffic Safety Administration (NHTSA)
21. U.S. Naval Surface Warfare Center (NSWC)
22. Verband der Automobilindustrie (VDA) (Germany)

- Contact Information:

  American Institute of Aeronautics and Astronautics

  1801 Alexander Bell Drive

  Reston, VA 20191

  http://www.aiaa.org/default.aspx

- AIAA is working on a new battery safety standard.

- AIAA has earned an international reputation as the preeminent publisher of cutting-edge aerospace books and journals, and the leading source of aerospace industry archives, dating back to the early 1900s. Over the past eight decades, AIAA and its predecessor organizations have published over 300 books and almost 200,000 technical articles. AIAA's current publications include seven technical journals, a magazine, three book series, national and international standards documents, a growing number of e-books and other electronic products, and a full-service, interactive Web site.

American National Standards Institute (ANSI)

- Contact Information:

Washington, DC Headquarters
1899 L Street, NW
11th Floor
Washington, DC, 20036
Tel: 202.293.8020
Fax: 202.293.9287

- ANSI oversees the creation, promulgation and use of thousands of norms and guidelines that directly impact businesses in nearly every sector: from acoustical devices to construction equipment, from dairy and livestock production to energy distribution, and many more. ANSI is also actively engaged in accrediting programs that assess conformance to standards – including globally-recognized cross-sector programs such as the ISO 9000 (quality) and ISO 14000 (environmental) management systems.

Activity in EV and HEV standards:

- In March 2011, ANSI created an **Electric Vehicles Standards Panel (EVSP)** that is very active. The work was initiated by a request from the US Department of Transportation (DOT). The initial goal is to understand all existing regulations as well as those in preparation. Then the group will prepare a roadmap for standards for the EV and HEV industry and highlight needs and identify gaps.

- The most recent meeting was June, 2011 in Detroit, MI. The participation is large, and includes electrical equipment manufacturers, US Government agencies and standards-making organizations. I am most familiar with the energy storage group, which is meeting every 2 weeks. It is important to realize that the likely direction of this effort by ANSI is to function as an accrediting agency for test programs that are in existence, rather than attempt to draft new test standards.

American National Standards Institute (ANSI)

EVSP Membership

- Alliance of Automobile Manufacturers
- Association of Global Automakers
- ATIS
- Audi AG
- Better Place
- California Public Utilities Commission
- Con Edison
- Corning Inc.
- CSA America
- Duke Energy
- Eaton
- Edison Electric Institute
- Electric Power Research Institute
- General Electric
- General Services Administration
- Green Dot (Transportation) Inc.
- Hubbell
- IEEE
- International Assn of Electrical Inspectors
- International Code Council
- Intertek
- ITT Interconnect Solutions
- Mercedes-Benz USA
- National Electrical Contractors Assn
- National Electrical Manufacturers Assn
- National Fire Protection Association
- National Institute of Standards & Technology
- Rocky Mountain Institute
- SAE International
- Schneider Electric
- SEW-Eurodrive
- Siemens
- Sony Electronics, Inc.
- Southern California Edison
- Southern Company
- TDI Power
- Underwriters Laboratories, Inc.
- U.S. Department of Energy
- Virginia Tech Transportation Institute

- China (PRC) has developed quality/safety regulation that applies to cells, modules and batteries for various applications.
  - Automotive Industry Standard of the People's Republic of China is QC/T 743-2006 "*Lithium-Ion Batteries for Electric Vehicles*"
    - Published by National Development and Reform Commission in 2006, and was being revised in 2012.
    - Based heavily on J2464.
  - Standardization Administration of China (SAC) announced the publication of GB 31241-2014 "*Safety Requirements for Lithium Ion Cells and Batteries Used in Portable Electronics*" which came into force on Aug 1st, 2015.

- Contact Information:

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  http://www.iata.org

- IATA is a trade association of the world's airlines. It supports airline activity and helps formulate industry policy and standards.

- IATA is headquartered in Montreal, Canada with Executive Offices in Geneva, Switzerland

International Electrotechnical Commission (IEC)

- Contact Information:

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Switzerland
Tel: +41-22-919-02-11
www.iec.ch
http://webstore.iec.ch/Webstore/webstore.nsf/Homepage?ReadForm

- IEC has been very active in developing safety and abuse tolerance test standards.
- IEC typically focus on cell and small battery pack safety, whereas ISO focuses on large battery pack safety and abuse tolerance tests.

These two standards are important in that they are almost universally accepted for the markets that they address. While these standards do not apply to EV and HEV batteries, the test methods are important reference points for any standard that evaluates battery safety.

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