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Battery Safety & Abuse Tolerance Test Procedures

for Electric and Hybrid Electric Vehicles -

Comparison and Analysis of Published Test Methods

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Outline

- Importance of battery safety.
  - Goals of test programs.
  - Safety and Abuse Tolerance Testing vs. “Field Failure”.
- Types of safety and abuse tolerance tests that are appropriate for energy storage devices.
  - Organizations that are developing standards.
- Approach to Test Method development.
  - “Pass/Fail” vs. “Characterization Tests”
- Comparison of Test Methods.
- Internal Short Circuit Tests under Development.
- Failure Propagation Test.
- Summary.

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Safety and Abuse Testing of Batteries is of Central Importance

- Safety, along with cost and life, is a continuing concern.
  - The safety of large cells and large capacity batteries, such as used for vehicle traction, is more difficult to manage than small cells and batteries.
  - Use environments can be challenging (temperature, vibration, etc.)
- Safety is a systems issue, with many inputs and factors.
  - “Safe” cells and batteries can be unsafe in applications because of poor engineering implementation or incomplete understanding of system interactions.
- Standardized tests are crucial to obtain a fair comparison of different technologies and to gauge improvements.
  - Outcome of safety and abuse tolerance tests is STRONGLY INFLUENCED by experimental conditions.
  - Standardized tests can remove most to the variability.

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Goal of Safety and Abuse Tolerance Testing

- Characterize the battery response to undesirable abusive conditions also termed “off-normal” conditions or environments that may arise as a result of:
  - device or system defects,
  - operator negligence,
  - accidents,
  - poorly informed or trained users or mechanics,
  - failure of specific battery control & support hardware, or
  - transportation/handling incidents or accidents.

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Comparison of Abuse Testing to Field Failure

- ***Abuse Test Failure can be systematically investigated.***
  - Mechanical
    - **crush, nail penetration.**
  - Electrical
    - **short circuit, overcharge.**
  - Thermal
    - **thermal ramp, simulated fire.**
- ***Field Failure is Unpredictable***
  - Manufacturing defects
    - **Loose connection, separator damage, foreign debris.**
    - **Failure may only occur in aged, used cells.**
    - **May develop into an internal short circuit.**
    - **Results in overheating and cell failure.**

SNC-Lavalin Gulf Contractors Safety Alert, June 2008

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Impact on Transportation Industry

Incidents of cell field failure from manufacturing defects are low – cell failures rates are approx. 1 in 5 to 10 million or less, but…

- The numbers of cells used potential in the automotive industry (PHEVs and EVs) is huge (billions).
- There are 250 million cars on the road in the USA.
- PHEV and EV battery packs are large (15 to 56 kWh)

Example: Tesla Roadster

- 56 kWh lithium ion battery pack . (~6800 Li Ion 18650 cells).
- 1,200 Roadsters sold (July 2010) → 8.16 M cells!!

How should we scale failure rates observed in small cells – per cell, per electrode area, per length of electrodes?

www.teslamotors.com and www.edmonds.com

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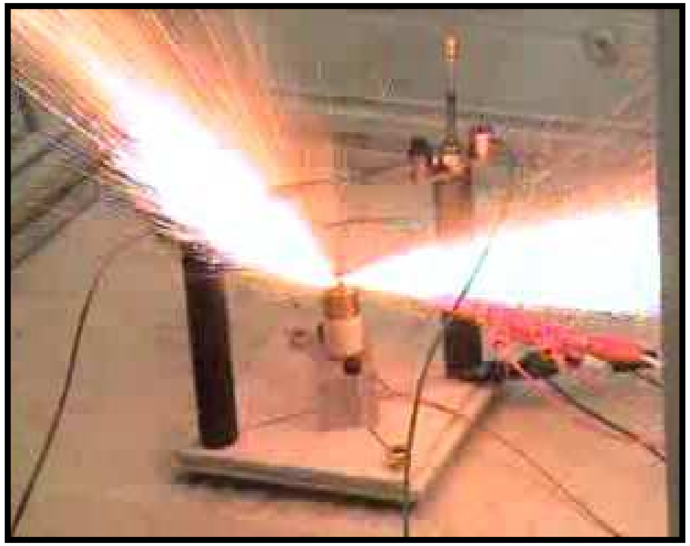
Types of Abuse Testing

- **Mechanical Abuse**
  - **Mechanical Shock Test**
  - **Vibration**
  - **Drop Test**
  - **Penetration**
  - **Immersion**
  - **Crush**
- **Thermal Abuse**
  - **Simulated fuel fire**
  - **Thermal Stability**
  - **Accelerating Rate Calorimetry**
  - **Overheat/Thermal Runaway**
- **Electrical Abuse**
  - **Short Circuit**
  - **Overcharge**
  - **Overdischarge**



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Battery Safety Standards in Revision or Development By Many Organizations

SAE International

IEEE Advancing Technology for Humanity

IEC

ISO International Organization for Standardization

UL the standard in safety

JARI-RB

- SAE J2464 published in Nov. 2009 "***EV & HEV Rechargeable Energy Storage System (RESS) Safety and Abuse Testing Procedure***".
- SAE has published J2929, "***Electric and Hybrid Vehicle Propulsion Battery System Safety Standard***", a pass/fail standard for battery packs in Feb. 2011.
- IEEE 1625 published in October 2008 "***Standard for Rechargeable Batteries for Multi-Cell Mobile Computing Devices*". **
- IEEE 1725 published in March 2006 "**IEEE Standard for Rechargeable Batteries for Cellular Telephones"** and is under revision again.
- IEC 62660-02 "***Secondary Batteries For The Propulsion of Electric Road Vehicles***" is under development.
- ISO /CD 12405-2 "***Electrically Propelled Road Vehicles — Test Specification For Lithium-ion Traction Battery Packs And Systems***" is under development.
- UL 2580 "***Batteries For Use In Electrical Vehicles***" is under development.
- VDA (Europe) published ***"Test Specification For Li-ion Battery Systems For Hybrid Electric Vehicles"*** in March, 2007
- JARI (Japan Automobile Research Institute) is developing standards.

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Approaches to Test Method Development

- ***Characterization Tests*** provide valuable data and information
  - in early stage of development and
  - as input to Risk Management Analysis.
    - See "Battery Safety and Hazards Risk Mitigation" formalism developed for USABC
      - http://www.uscar.org/guest/article_view.php?articles_id=86
    - Approach is used by SAE, IEC and ISO.
- ***Pass/Fail Tests*** are appropriate for mature technology and for shipping standards.
    - Approach used by NHTSA, UN, UL, ANSI and IEEE.
    - SAE has initiated development of a Pass/Fail standard for vehicle batteries.

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Test Methods And Conditions - Comparison Between Standards

- Each test method tries to develop tests that are specific to the particular use environment.
    - UN shipping tests requires short circuit on cycled cells.
    - IEEE laptop computer batteries requires float charge test.
    - SAE Vehicle Battery Test require monitoring of hazardous gas.
- Some standards are give design guidance (IEEE and UL) and others have test definitions.
- Some similarities exist.
  - Sometimes identical test conditions
    - High altitude test exposure.
  - Standards may cross-reference other standards.

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Status of Test Harmonization

- My judgment is “fair to poor”.
  - Each organization seems to want to do the tests in a different manner.
  - Little incentive to reach agreement on harmonized wording, except for a few organizations that have prior agreements – e.g., UL and IEC.
- The following slides give **overview of key element in several standards**, focusing on the abuse test standards for Automotive Traction Batteries.

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Comparison Table #1 Electrical 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
External Short Circuit	X	X	X	X	X	X	X	X
Overcharge	X	X	X	X	X	X	X	X
Overcharge Protection Evaluation						X		
Forced Discharge (Over-discharge)	X	X	X	X	X		X	
Overdischarge Protection Evaluation						X		

- **There is universal acceptance of short circuit and overcharge, but tests are done differently.**
- **Increasing emphasis on tests of quality/function of protection circuitry.**

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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.**
- **Often the tests are done differently.**

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Comparison Table #3 Thermal 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
Temp. Cycling (Thermal Shock)	X	X	X	X	X	X		
High Temperature		X		X				
High Temp. Storage							X	
High Rate Discharge w/o Cooling		X	X					
Open Flame Test (Fuel Fire or "Projectile")		X	X			X	X	
Cycling w/o Thermal Management		X				X		
Hazardous Substance Monitoring		X				x		
Separator Shutdown		X						
Fault Analysis			X			X		
Propagation Resistance		X				X		

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There is No Agreement on Hazard Severity Score

The relative importance of fire/flame and venting is viewed differently.

Hazard Level	EUCAR Description	SAE J2464 Description	IEC Description
0	No effect	No effect	No effect
1	Passive protection activated	Passive protection activated	Deformation
2	Defect/Damage	Defect/Damage	Venting
3	Leakage (Δ mass < 50%)	Minor Leakage/ Venting	Leakage
4	Venting (Δ mass ≥ 50%)	Major Leakage/ Venting	Smoking
5	Fire or Flame	Rupture	Rupture
6	Rupture	Fire or Flame	Fire
7	Explosion	Explosion	Explosion

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What are Important Issues and Current Topics?

- Internal short circuit tests.
  - Several organizations are trying to develop propagation tests:
    - JARI
    - UL
    - NASA
    - Motorola, etc.
- Propagation tests.
  - Only SAE J2464 (EV & HEV Abuse Tests) and UL 2580

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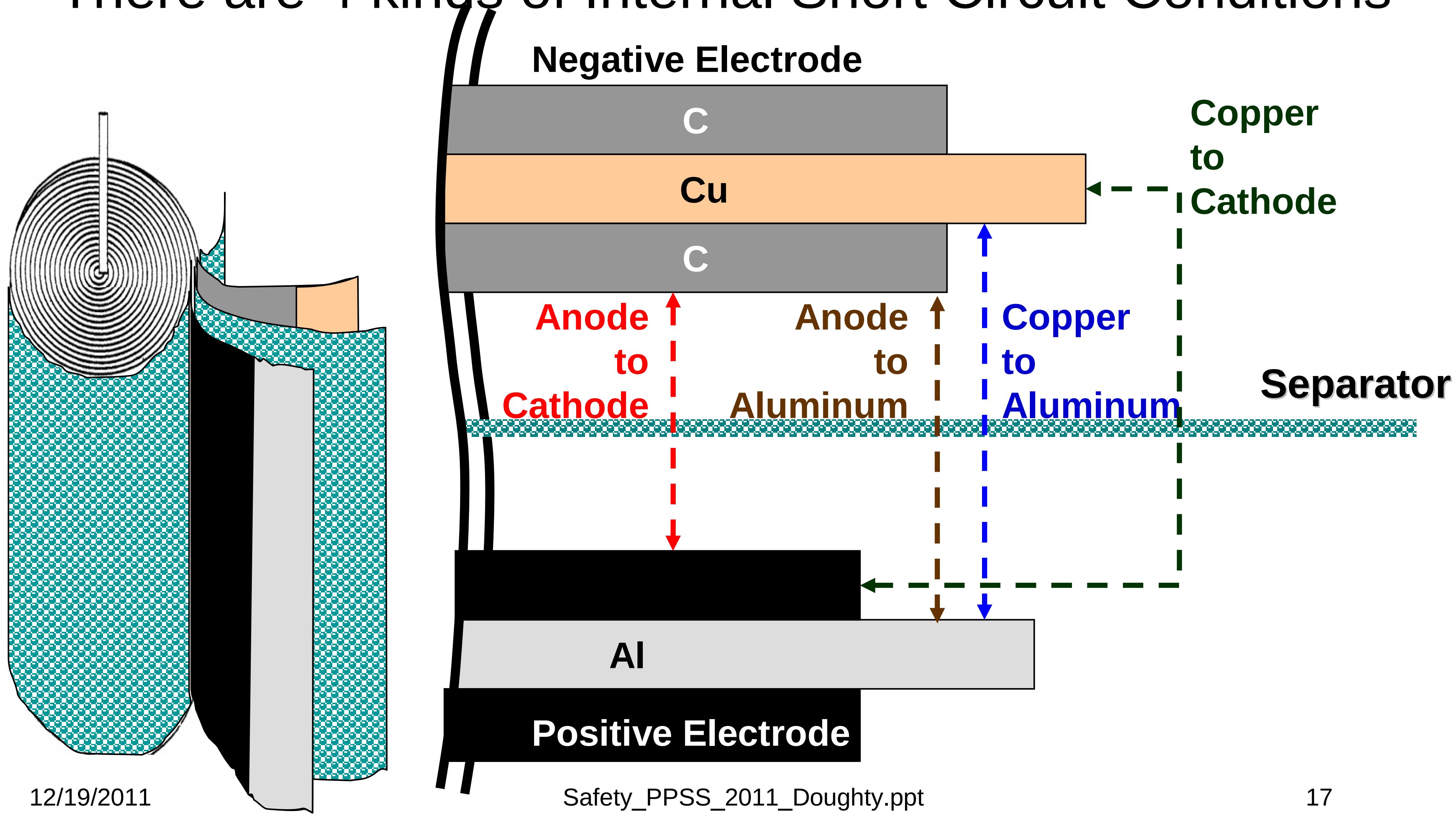
Sources of Internal Short Circuit Test Variability

There are 4 kinds of Internal Short Circuit Conditions



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Internal Short Circuit Tests under Development

- **No test has gained acceptance of many industry or test organizations.**
  - UL Blunt Nail Crush (BNC)
    - Crush the cell with a Blunt Nail until detection of 100 mV open circuit voltage(OCV) drop.
      - PRO: Method does not require a lot of special sample preparation.
      - CON: Short Mechanism depends on how blunt nail interacts with internal construction.
  - NASA Blunt Nail method.
    - Some similarities to UL BNC test.
      - Pass/Fail depends on vibration tests after BNC.

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Internal Short Circuit Tests under Development

- Japanese JIS C8714 method: Forced Internal Short-Circuit Test
  - Disassemble charged cell, insert L-shape nickel metal particle, reassemble cell and test.
    - PRO: Can control location of internal short circuit.
    - CON: Does not apply to polymer cells and is unsafe for large format cells.
      - » Requires special equipment and cell preparation facilities. Difficult to perform.
- Saft – Internal Heater Wire
  - Heater wire inserted into cell. Apply current (external power supply), separator melts & short circuit ensues.
    - PRO: Can control location of internal short circuit.
    - CON: Heating too diffuse – behaves like internal thermal ramp test.

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Internal Short Circuit Tests under Development

- SNL – thermal trigger w/low temp melting alloy
  - incorporate low melting temperature (~65℃) alloy particles during cell winding.
    - PRO: Can produce internal short circuit in 18650.
    - CON: elevated temperature required & result depends on cell geometry (cylindrical vs. prismatic).
- Motorola/Oak Ridge Nat's Lab pressure test
  - Two spheres are placed on opposite sides of prismatic cell and press on cell.
    - PRO: can cause internal short circuit in internal winding layers.
    - CON: can't be used on cylindrical cells.

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My Opinion on Internal Short Circuit Tests

- Useful in the development of more abuse tolerant cells.
  - Cell manufacturer should try to perform internal short circuit test 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.
  - Can't be used on all cells.
  - Irreproducible results & difficult to control.
    - Spiral vs. planar geometry; cell construction variables.
  - Safety Issues of performing the test.
  - Blunt Nail deforms the battery case.
    - Compromises cell integrity.

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How Can Tests for Internal Short Circuit be Addressed?

- Internal short circuit outcome may be benign but also may trigger thermal runaway.
  - Very low probability event – failure rate estimated to be 1 in 5-10 million cells.
  - Worst outcome (cell level) is one cell vents and burns.
- In advance, we don't know when or if thermal runaway of a cell will occur
  - This type of failure cannot be predicted or screened by cell acceptance testing methods in use today.
  - Difficult to reproduce in lab setting.
    - Several organizations are working to develop internal short circuit screening tests.

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The Goal is to Confine the Damage to One Cell

- Failure of one cell should be contained by battery pack.
- Failure of one cell cannot cause destruction of entire battery pack.
- Propagation test is the only way to evaluate this possible outcome.
  - Packs have successfully passed this test.
- Particularly important for large format applications like vehicles and stationary applications.

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Failure Propagation is a Real Phenomenon

- 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.
- Has 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.

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Example of Propagation of Cell Failure

- Video of Lithium ion rechargeable batteries module.
- Pack failure during short circuit. Propagation mechanism observed in other configurations and with other chemistries.

Thanks to C. Orendorff, SNL, for supplying the video.

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Definition of "Propagation Resistance" in SAE J2464

- The Propagation Resistance test evaluates the ability of a test article to withstand a single cell thermal runaway event.
  - The RESS is heated to the maximum operating temp.
  - One cell within the RESS is driven to thermal runaway
    - Can be heated *in-situ* in less than 5 minutes to a temperature of 400℃ or overcharged.
    - Repeated using cells in other locations.
  - Module or pack is observed to determine the extent of failure propagation to adjacent cells in the RESS.
- Propagation has not been included in SAE J2929.
- Propagation has been included in UL 2580 and is in consideration for ISO 62619 (Li Rechargeable for Industrial (Stationary) application - DRAFT)

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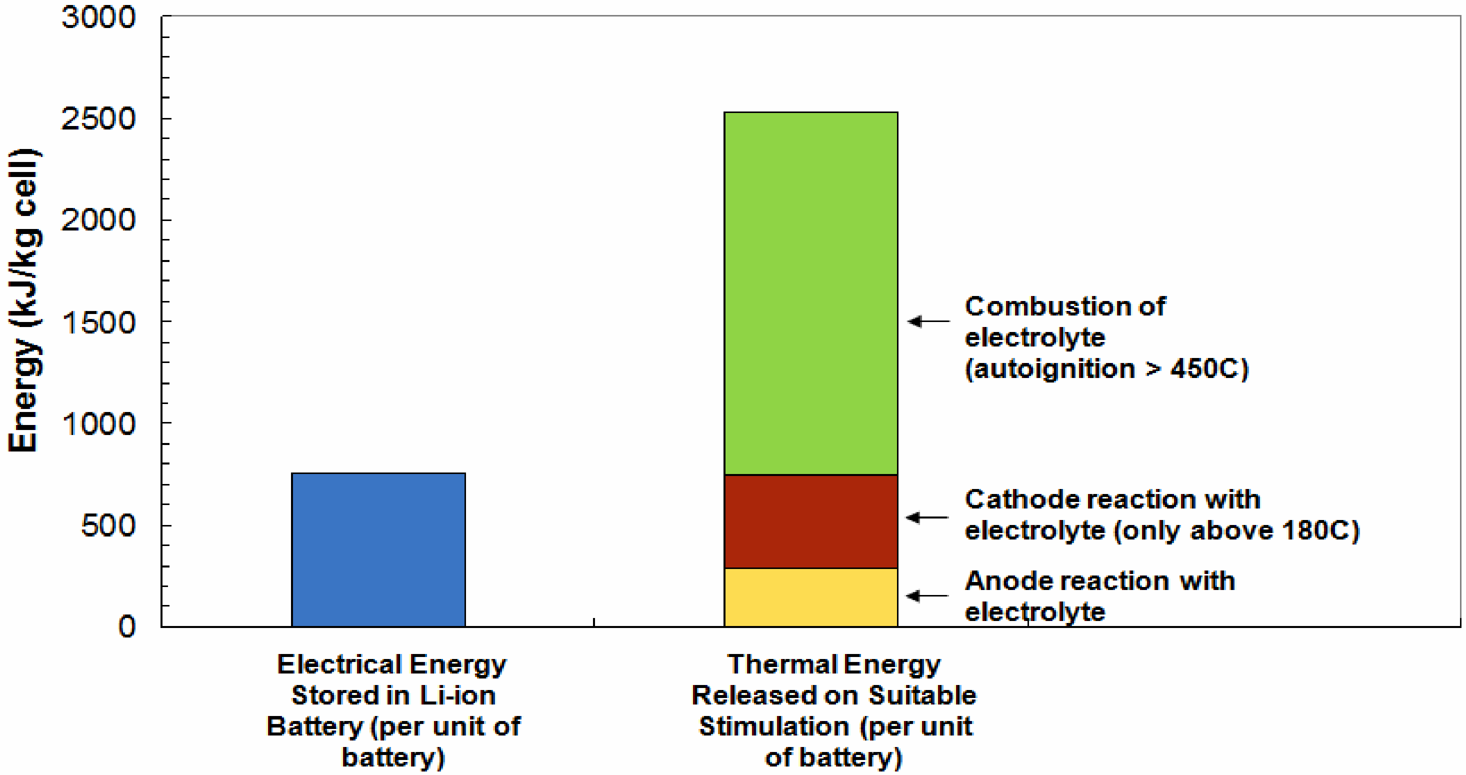
What is Completely Missing from Safety Standards?

- **Flammability test for electrolytes.**
- When the electrolyte burns, it releases 2x to 3x the amount of stored electric energy, making a bad situation worse.



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Summary

- Battery safety is of central importance to the industry.
  - Batteries have good safety record, but it can get better.
  - The proliferation of battery powered devices and battery powered vehicles adds urgency to this effort.
  - The safety of high energy and large format batteries is more difficult to manage.
- Abuse tolerance test standards have key role in evaluating the safety of batteries.
  - Test procedures have matured and give reliable results.
- Many organizations worldwide are developing standards. Harmonization should be higher priority.
  - Characterization Tests and Pass/Fail Tests are available.
  - Several organizations are developing standards for EV/PHEV applications.

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- SAE Team Members who dedicated their time and energy to improving J2464.
- Former Colleagues at Sandia National Labs.
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Thank You.