

# ***Sandia Battery Abuse Testing Laboratory (BATLab)***

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Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.





# Cell Failure Modes

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## Field Failure Consumer Electronics

- **Field Failure**

- **Manufacturing defects**

- Loose connection, separator damage, foreign debris
    - Can develop into an internal short circuit
    - Can lead to overheating and thermal runaway



- **Abuse Failure**

- **Mechanical**

- crush, nail penetration

- **Electrical**

- short circuit, overcharge

- **Thermal**

- thermal ramp, simulated fire



# ***Differences Between Abuse Tolerance and Field Failures***

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- There are important differences between safety-to-withstand abuse, versus safety-to-withstand field failures.

Abuse Tolerance	Field Failures
<ul style="list-style-type: none"><li>◆ Predictable</li><li>◆ Common to all cells</li><li>◆ Can/should be evaluated at the cell level</li><li>◆ Various chemistries can/should be evaluated for relative abuse tolerance</li><li>◆ Time constants relatively long</li><li>◆ Can be augmented by protection devices</li></ul>	<ul style="list-style-type: none"><li>◆ Not predictable</li><li>◆ One-in-a-million (or less)</li><li>◆ Difficult to evaluate at the cell level, or through QC</li><li>◆ Materials must be evaluated for relative kinetics, pressures</li><li>◆ Much higher temperatures can occur <i>quickly</i></li><li>◆ PTC, CID, shutdown separators, electronic controls are not effective</li></ul>



# Impact on Transportation Industry

**Incidents of cell failure from manufacturing defects are 1 in 5 million, but...**

- *The numbers of cells used potential in the automotive industry (EVs and PHEVs) is huge (billions)*
- *There are 250 million cars on the road in the US*
- *EV and PHEV battery packs are much higher energy (15-50 kWh)*

## Tesla Roadster

- 50 kWh lithium ion battery pack (6800 Li<sup>+</sup> cells)
- 1000 cars produced (April 2010)  
→ 6.8 M cells!!



## Prius Retrofit to PHEV

- LiFePO<sub>4</sub> cathode
- Investigation found that a loose connector was the fault point (nothing to do with the battery)
- Negative publicity is detrimental to the industry





# **DOE Vehicle Technologies Program Structure**

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- **Developer Program: US Advanced Battery Consortium (USABC)**
  - Develop electrochemical energy storage devices that meet USABC/FreedomCAR technical goals through cost-shared projects with industry
- **Applied Battery Research: Advanced Battery Research for Transportation Program (ABR)**
  - Address key cross-cutting barriers for lithium ion batteries to support the Developer Program
- **Focused Fundamental Research: Batteries for Advanced Transportation Technologies (BATT) program**
  - Conduct innovative, cutting-edge research on the next generation of lithium battery systems



**(SNL Battery Abuse Laboratory Participation)**



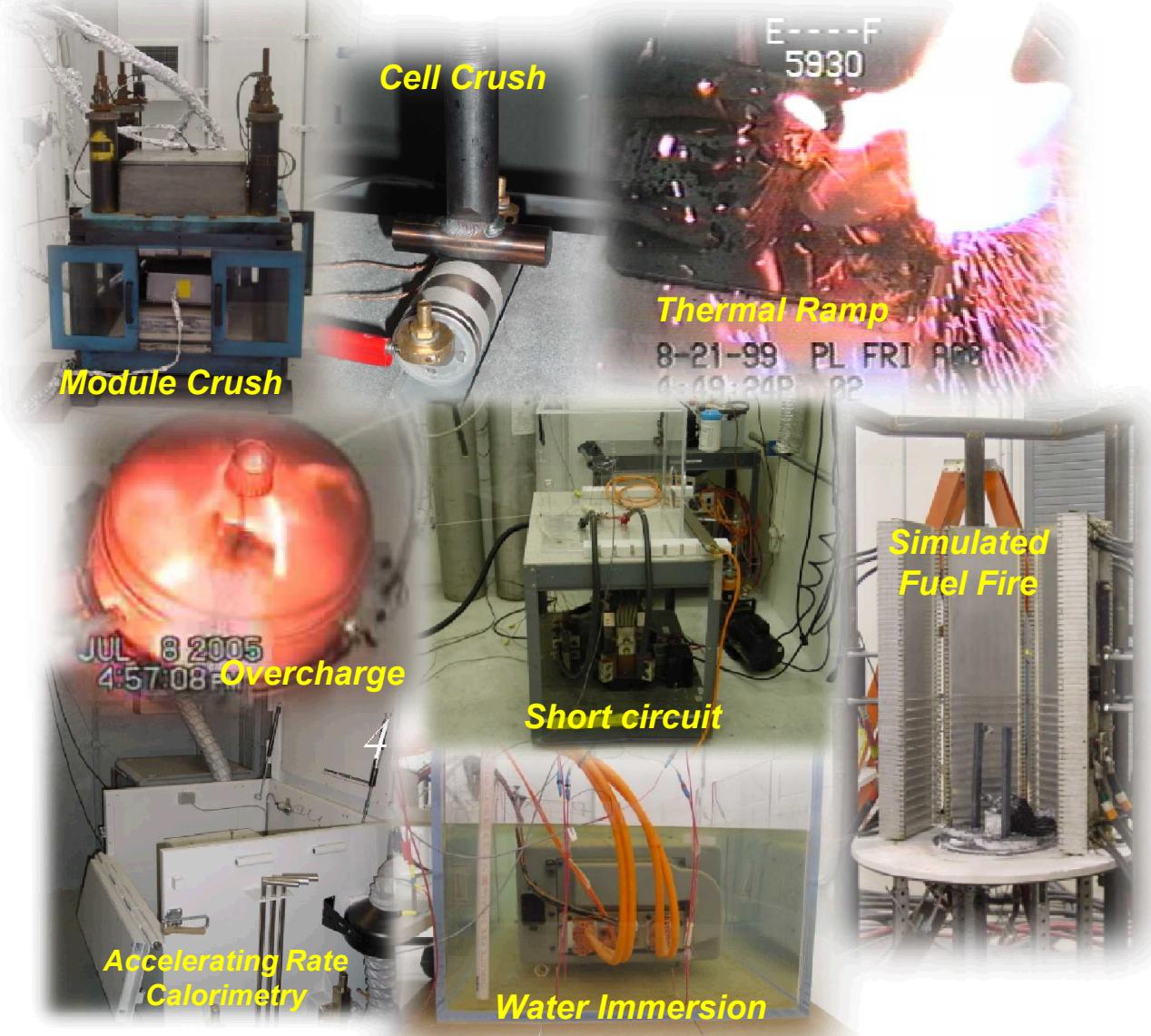
# **Description of Main Safety/Abuse Tolerance Studies**

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- **SNL is investigating the abuse tolerance of lithium-ion cells and batteries (and other types of chemistries) for the DOE**
  - Investigation of prototype cells to develop mechanistic understanding of abuse response
- **Testing of pre-production battery packs being developed for the DOE's USABC program**
  - SNL staff wrote the Abuse Test Manual for electric Vehicle Batteries used by the Society of Automotive Engineers (SAE J2464)
  - Information is proprietary
- **Understand mechanisms that lead to poor abuse tolerance**
  - Thermal runaway & gas generation
  - Abuse environments include thermal, electrical & physical abuse
    - **High Temperature** ramp and thermal stability are the most common thermal abuse
    - **Overcharge** and **Short Circuit** are most common electrical abuse
    - **Crush and Nail Penetration** are the most common physical abuse

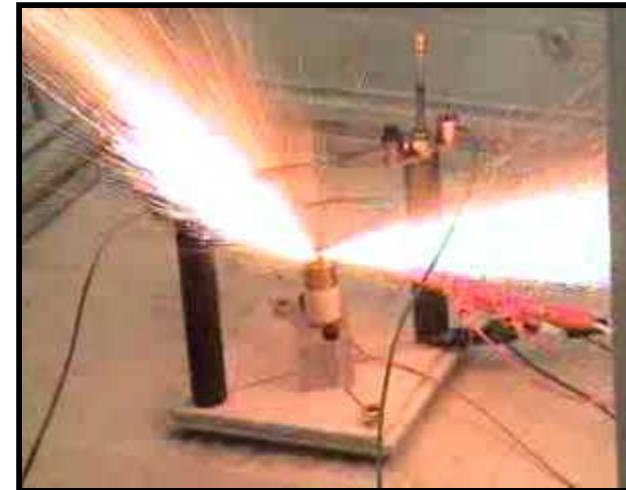


# Examples of Sandia Battery Abuse Laboratory Capabilities



# *Testing Done in Accordance with SNL Abuse Manual and SAE J2464*

- **Mechanical Abuse**
  - **Mechanical Shock Test**
  - **Vibration**
  - **Drop Test**
  - **Penetration**
  - **Immersion**
  - **Crush**
- **Thermal Abuse**
  - **Radiant Heat (simulated fuel fire)**
  - **Thermal Stability**
  - **Accelerating Rate Calorimetry**
  - **Overheat/Thermal Runaway**
- **Electrical Abuse**
  - ***Short Circuit***
  - ***Partial Short Circuit***
  - ***Overcharge***
  - ***Over-discharge***



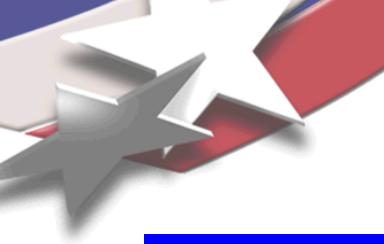
(Tests performed at the SNL BATLab)  
(Tests performed at other SNL facilities)



# *Abuse Testing Allows Comparison Of Technologies And Failure Modes*

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- Define conditions that are likely to cause problems.
  - Crush, elevated temperature, overcharge are examples.
- Expose test units to these conditions and monitor response.
  - Very likely to observe failures.
- Document levels of stress that cause failure.
- Compare results for different mechanical designs and different choices of chemistry.



## ***The Purpose of Abuse Tests is to Evaluate the Response to Off-normal Environments That Might Trigger Exothermic Reactions Within Cell.***

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- PASS/FAIL testing is the type of approach that Underwriters Lab (UL) or United Nations (UN) defines.
  - Provides standard test that mature technologies must meet in off-normal environments.
  - Tests are conducted on the final assembly/battery configuration.
  - If the article passes the test, you don't learn about failure modes.
- CHARACTERIZATION tests which evaluate the response to abuse environments are more useful for developmental technology.
  - Usually results in failure of the test article.
  - Documentation of conditions that cause failure.
  - Evaluate failure modes and abuse conditions using destructive physical analysis.
  - Provide quantitative measurements of cell/module response.
  - Document improvements in abuse tolerance.
- As the technology matures, abuse testing will evolve from characterization to pass/fail tests.



# Testing Parameters

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- Level of Assembly
  - Initial tests of a given EESS design should be conducted at the lowest level of assembly (cell, module, or pack) for which meaningful data can be gathered.
- System Age
  - Initial tests of a given EESS design are generally conducted using a relatively new EESS (i.e., one that has not undergone cycle life testing or been extensively used).
  - Tests should be repeated on aged cells to verify tolerance of abusive conditions has not deteriorated.
- State of Charge
  - HEV and EV battery packs EESS should be tested at 100% SOC and unless specifically stated otherwise.



# *The Most Meaningful Subset of Tests for a Technology in a Developmental Stage*

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- Mechanical Abuse
  - **Controlled Crush**
    - Causes internal short circuit.
- Thermal Abuse
  - **Thermal Stability up to 200°C or 250°C**
    - Other types of abuse conditions often trigger a thermal abuse event.
- Electrical Abuse
  - **Overcharge/Overvoltage**
    - » May trigger thermal runaway
  - **Short Circuit**
    - » Not a problem for cells, but can be an issue in battery packs.



# ***Abuse testing is Performed to Characterize Response to “Off-normal Conditions”***

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**Assign Hazard Severity Level Score using descriptions adapted from EUCAR and SAND2005-3123**

<b>Hazard Level</b>	<b>Description</b>	<b>Classification Criteria, Effect</b>
0	No effect	No effect, no loss of functionality.
1	Passive Protection activated	No defect, no leakage, no venting, no fire or flame, no rupture, no explosion, no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed.
2	Defect / Damage	No leakage, no venting, no fire or flame, no rupture, no explosion, no exothermic reaction or thermal runaway. Cell irreversibly damaged, repair needed
3	Leakage $\Delta m < 50\%$	No venting, no fire or flame**, no rupture, no explosion, Weight loss < 50% of electrolyte weight. (electrolyte = solvent + salt)
4	Venting $\Delta m \geq 50\%$	No fire or flame**, no rupture, no explosion, Weight loss $\geq 50\%$ of electrolyte weight.
5	Fire or Flame	No rupture, no explosion, i.e., no flying parts.
6	Rupture	No explosion, but flying parts, ejection of parts of the active mass.
7	Explosion	Explosion, i.e., disintegration of the cell.



# ***Likelihood of Abuse Condition Is An Important Factor To Consider***

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- When judging the readiness of a candidate technology for deployment, it is useful to evaluate whether the tests could be characterized as
  - **“likely abuse”** - a condition that is likely to inadvertently occur during “normal” use (e.g., short circuit),
  - **“moderate abuse”** - an abuse condition that is not likely, or
  - **“extreme abuse”** - an abuse condition that is very unlikely.
- A catastrophic response of a cell or module (i.e., Response Level 6 or 7) to a “likely abuse” condition should be treated much more seriously than a catastrophic response of a cell or module to an “extreme abuse” condition.



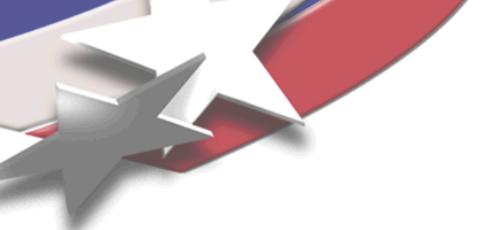
# *Abuse Response of Lithium Ion Modules Can be Catastrophic*

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**These pictures were taken after overcharge of a prototype  
HEV module at SNL Battery Abuse Testing Laboratory**

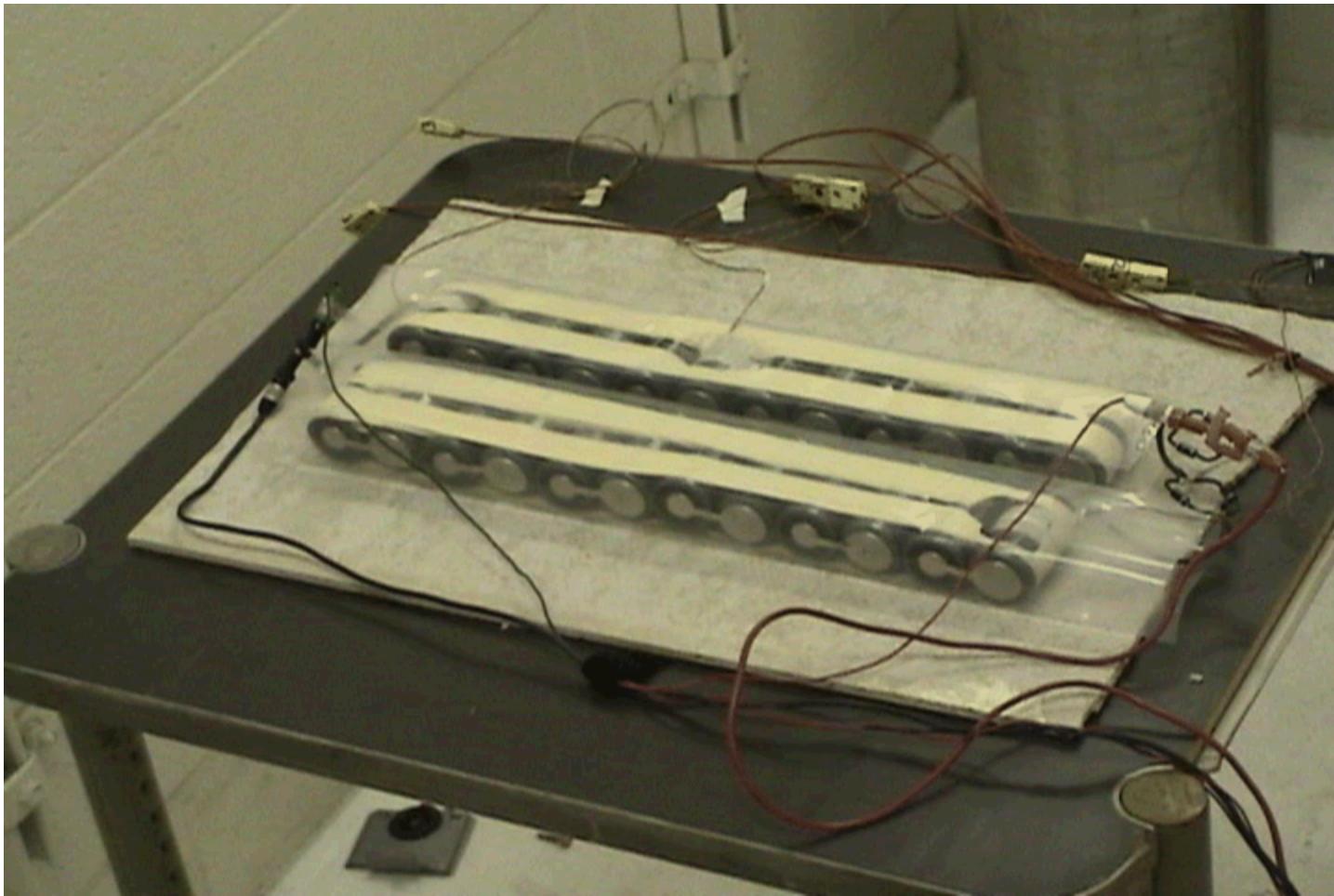


**Hazard Level 6 - Rupture**



# *Cascading Cell Failure in a Battery Pack*

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# *Cell Level Abuse Tests Are Often Performed During Initial Material Development Phase*

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## *Overcharge 18650 cell (in air)*

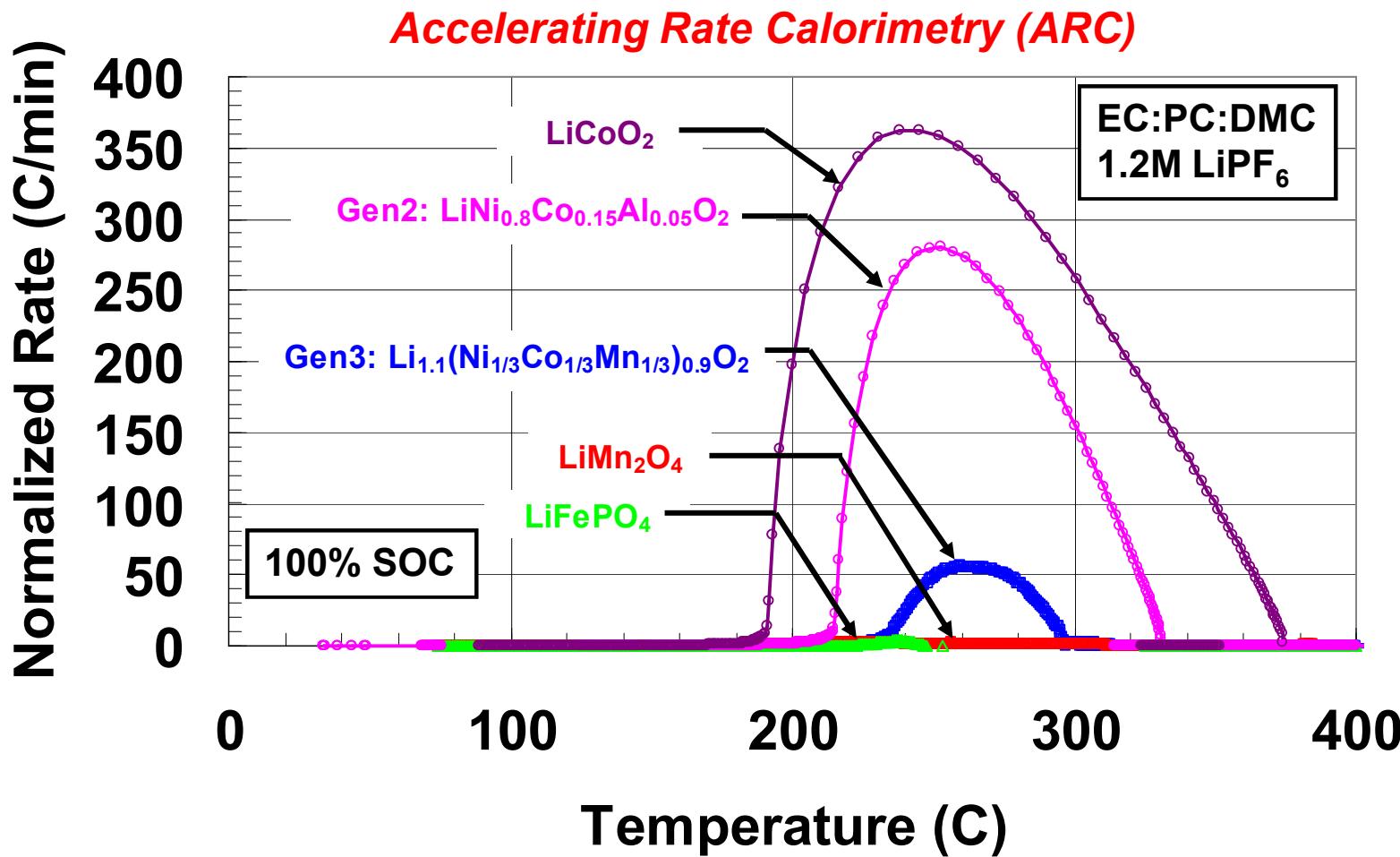


## *Overcharge Li-polymer pouch cell*



# Improving Cathode Stability

## New Abuse Tests Required for Each



- Increased thermal runaway temperature and reduced peak heating rate for full cells
- Decreased cathode reactions associated with decreasing oxygen release



# **New Abuse Test Manual**

## **Published by Society of Automotive Engineers**

### **SAE (www.sae.org) in 2009 (J2464)**

TAB	<b>SURFACE VEHICLE RECOMMENDED PRACTICE</b>	<b>SAE J2464 PropDft SEP2009</b>
	Issued Revised	1999-03 Proposed Draft 2009-09
		Superseding J2464 MAR1999
(R) Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing		

Product Code: **J2464** Date Published: 2009-11-06

#### **Issuing Committee:**

Vehicle Battery Standards Committee

#### **Scope**

This SAE Recommended Practice is intended as a guide toward standard practice and is subject to change to keep pace with experience and technical advances. It describes a body of tests which may be used as needed for abuse testing of electric or hybrid electric vehicle batteries to determine the response of such batteries to conditions or events which are beyond their normal operating range. This document is derived from a similar document originally developed by the U.S. Advanced Battery Consortium. (See 2.2.1.)



# Types of Abuse Tests Addressed in J2464

**TABLE 1 - RECOMMENDED AND OPTIONAL ABUSE TOLERANCE TESTS,  
INCLUDING THE NUMBER OF RESS CELLS, MODULES AND PACKS FOR EACH TEST**

Section	Recommended number of cells*		Recommended number of modules or packs <sup>(1)</sup>		
	Hazardous Substance Monitoring	Recommended Tests	Optional Tests	Recommended Tests	Optional Tests
4.2					
4.2.1.1	Electrolyte vapor RESS cell forced vent	2 <sup>(2)</sup> 6			
4.2.1.3	RESS cell forced vent with thermal runaway	2			
4.2.1.4	Pack level hazardous substance monitoring			1	
4.3	<b>Mechanical Abuse Tests</b>				
4.3.1	Shock	2		2	
4.3.2	Drop			1	
4.3.3	Penetration	2			2
4.3.4	Roll-over			2	
4.3.5	Immersion			2	
4.3.6	Crush	2 <sup>(3)</sup>			1 <sup>(3)</sup>
4.4	Thermal Abuse Tests	Recommended Tests	Optional Tests	Recommended Tests	Optional Tests
4.4.1	High Temperature Hazard Test			1	
4.4.2	Thermal Stability	2 <sup>(4)</sup>			
4.4.3	Cycling without Thermal Management			2	
4.4.4	Thermal Shock Cycling	2		2	
4.4.5	Passive Propagation Resistance Test			1	
4.5	<b>Electrical Abuse Tests</b>				
4.5.1	Short Circuit	2		2	
4.5.2	Overcharge	4		1	
4.5.3	Overdischarge (Forced Discharge)	2			1
4.5.4	Separator Shutdown Integrity	2			



## **New SAE Standard, J2929, “Electric and Hybrid Vehicle Propulsion Battery System Safety Standard” Being Developed**

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- **J2929 is a follow-up to J2464 that will establish pass/fail criteria for automotive battery packs**
- **This SAE Standard will define a minimum set of acceptable safety performance criteria for a battery system to be considered for use in a vehicle propulsion system**
- **Target date for availability is Fall, 2010**



# ***International meetings have been held to discuss harmonizing testing standards***

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(for example: Jan. 20-23, 2009, Tokyo, Japan)

**(ISO is focused on battery pack/systems at the vehicle level and IEC at the cell and module level)**



- International Electrotechnical Commission (IEC)
  - The IEC is the leading global organization that prepares and publishes international standards for all electrical, electronic and related technologies. These serve as a basis for national standardization and as references when drafting international tenders and contracts.



- ISO (International Organization for Standardization) is the world's **largest developer** and publisher of **International Standards**.
  - ISO is a **network** of the national standards institutes of **163 countries**, one member per country, with a Central Secretariat in Geneva, Switzerland, that coordinates the system.



# *Summary*

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- New high-energy cells, modules and packs present a serious safety issue for use in commercial vehicles
- New abuse test procedures (J2464) have been developed through the SAE that can serve as a basis for testing standards
- Safety testing facilities, techniques and standards need to continue to be developed to meet the demands of new battery materials and designs