Internal Short Circuit: Take-away

- The **cell screening methods** and criteria in cell manufacturing and battery manufacturing facilities should be **extremely stringent**.
- Cells should be **screened before being assembled into batteries**. It is not advisable to assemble batteries with cells at the “as-received” SOC –this indicates they are not cycled or tested/screened before they are configured into batteries which could lead to catastrophic failures in the field.
- Cells and batteries should be **used conservatively within their specifications**.

Publication:

J. Jeevarajan et al., Are Soft Short Tests Good Indicators of Internal Li-ion Cell Defects?”, Proceedings of Battery Safety 2013, November, 2013.

High and Low Temperature Hazards

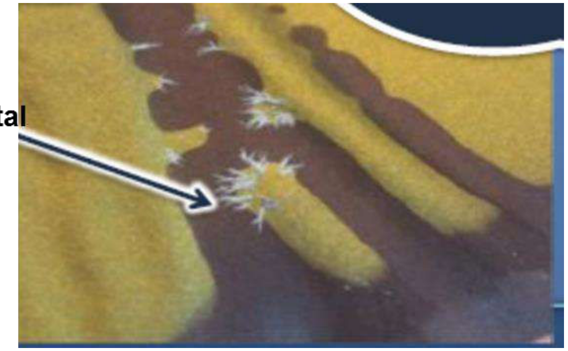
High Temperatures:

- Electrolyte decomposition and gas production
- Cathode and anode destabilization
- Can lead to venting and fire

Low Temperatures:

- Electrolyte viscosity increases
- Increases resistance for the flow of ions
- Can result in lithium metal dendrite formation

Lithium metal dendrites



- Test to characterize battery system at manufacturer's specified temperature extremes
- Confirm that battery system works in thermal environment of use

- Carry out destructive analysis to confirm that severe degradation had not taken place at the environmental use temperature
- Make changes to thermal conditioning design as needed

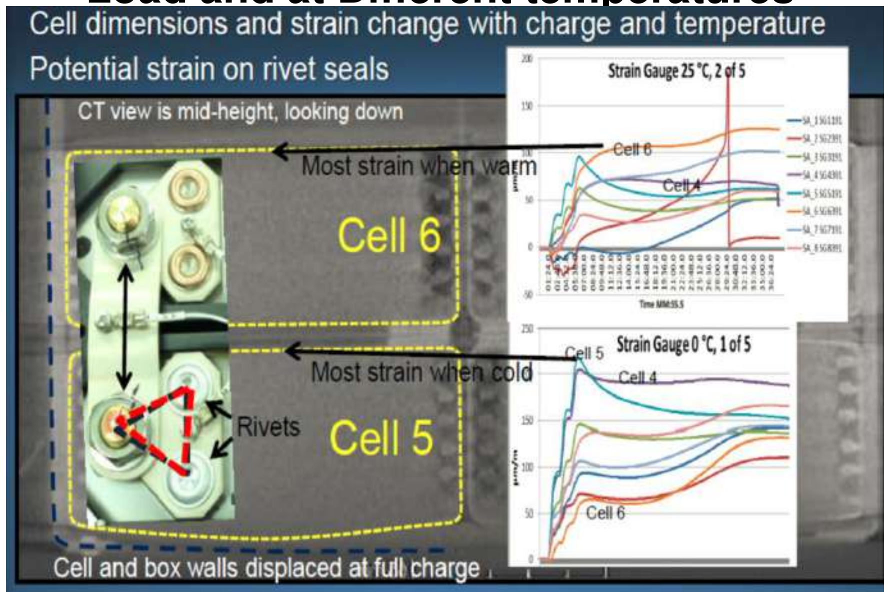
- Thermal gradient in the battery as a whole should be less than 5 deg F
- Thermal modeling will help provide better understanding of temperature dissipation and data on placement of thermal sensors

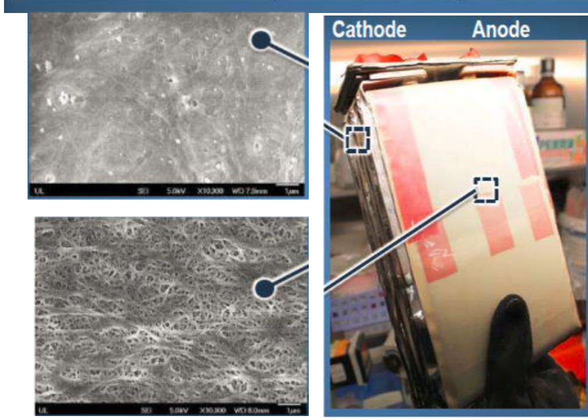
Take-away

Other Challenges – Destructive and Non-Destructive Analysis after Extreme Environment Tests?

Test at Cold Temperatures on Lithium-ion Cells

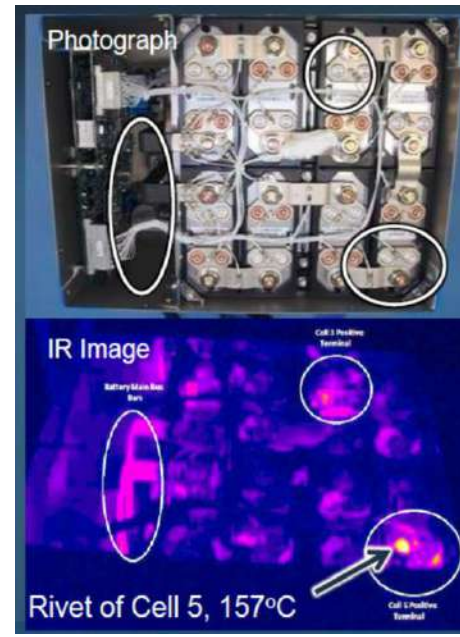
Cell Dimensions and Strain on Rivets under Load and at Different temperatures





APU Start Test for Boeing 787 batteries

Data from NTSB report on Boeing 787



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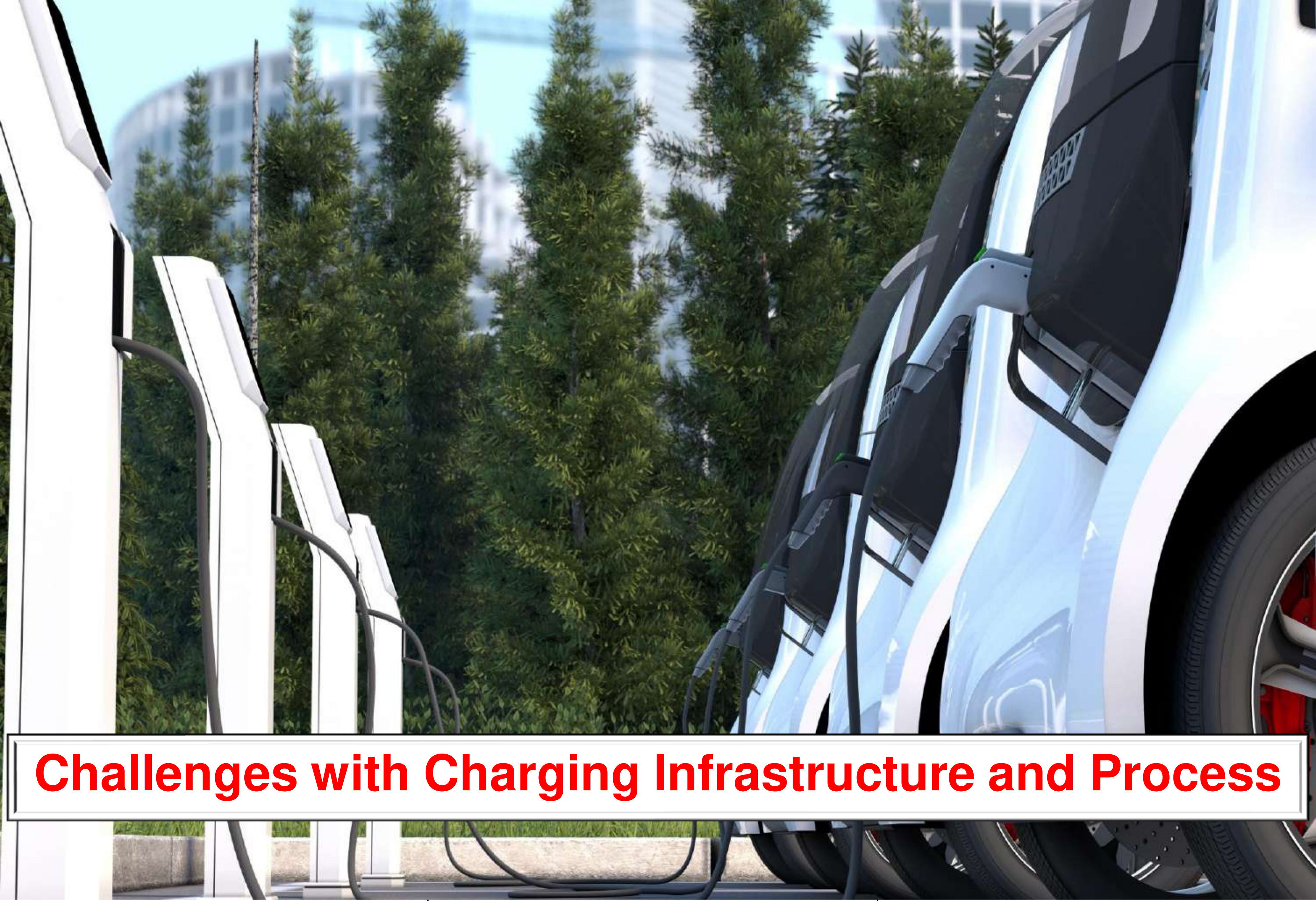

Challenges with Charging Infrastructure and Process

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Challenges with Charging Infrastructure and Process

- Business
  - Private ownership with private or public charging stations
  - Battery Swapping
- Technical
  - Recognition of correct Charge Protocol for the relevant Li-ion chemistry
  - State-of-health (SOH) determination
  - Age of batteries
- Regulations and Standards

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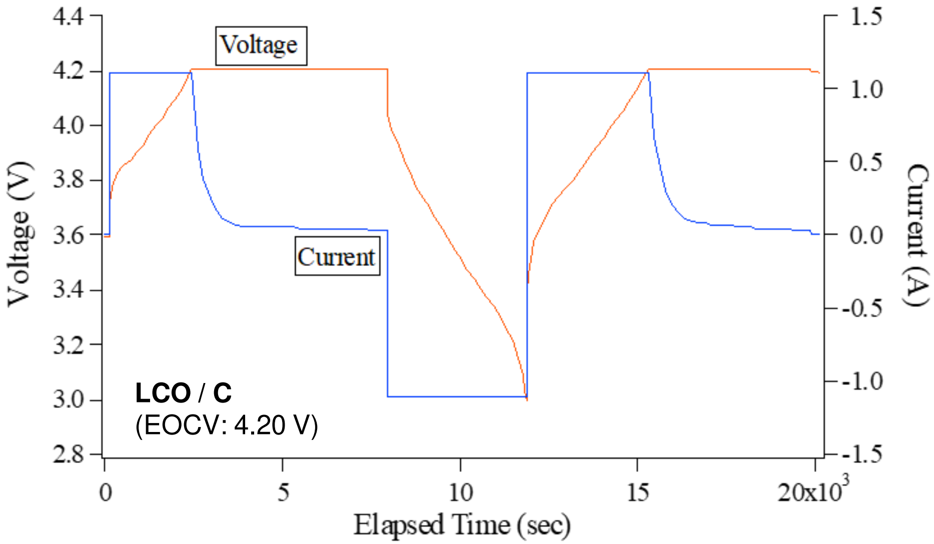
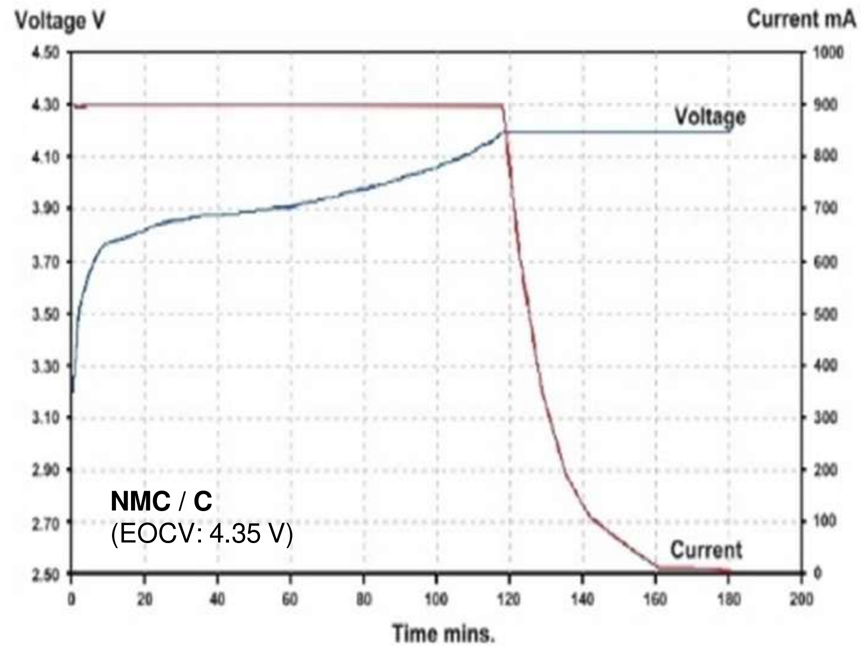
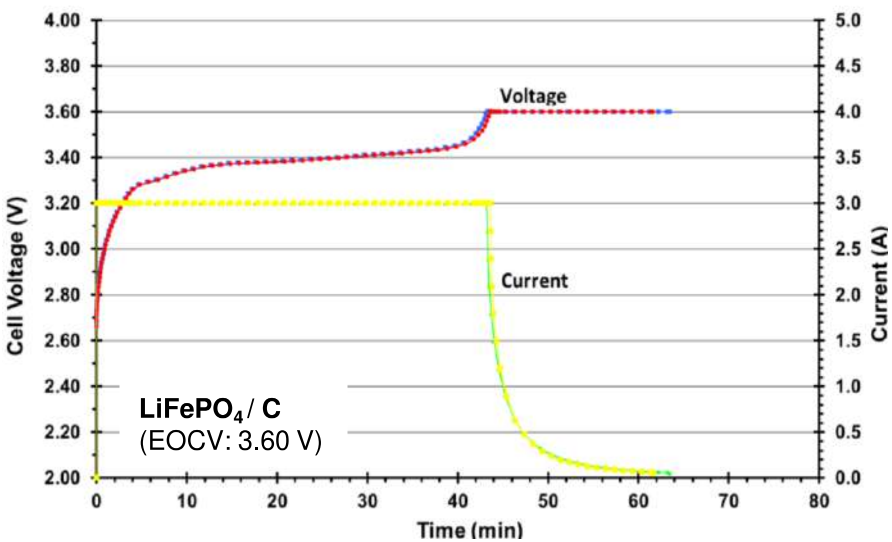
Charge Characteristics of Li-ion



Li-ion Charge Protocol:
Constant Current / Constant Voltage (CCCV)





Different cathodes for Li-ion cells have different end-of-charge voltages

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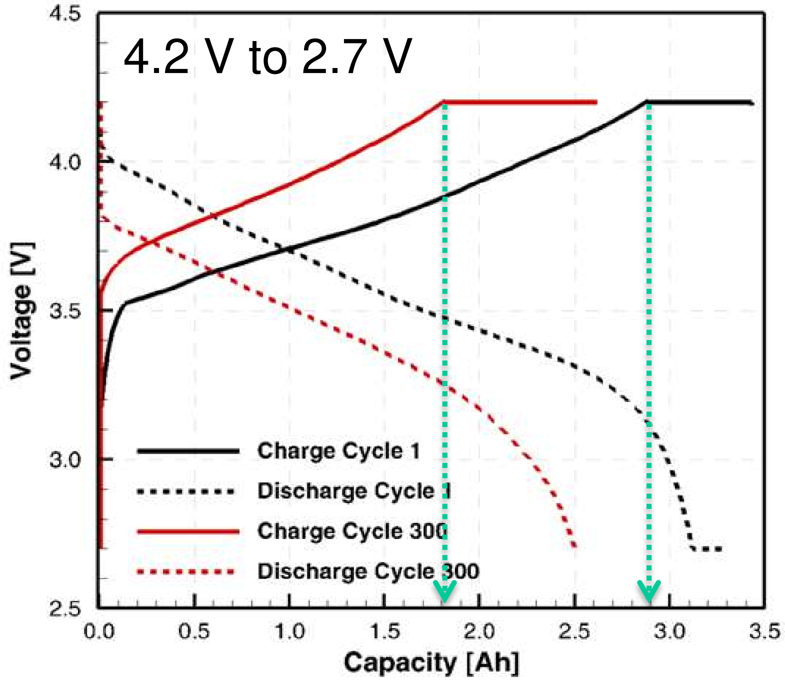
Comparison of Charge/Discharge Profiles of Fresh and Cycled Cells

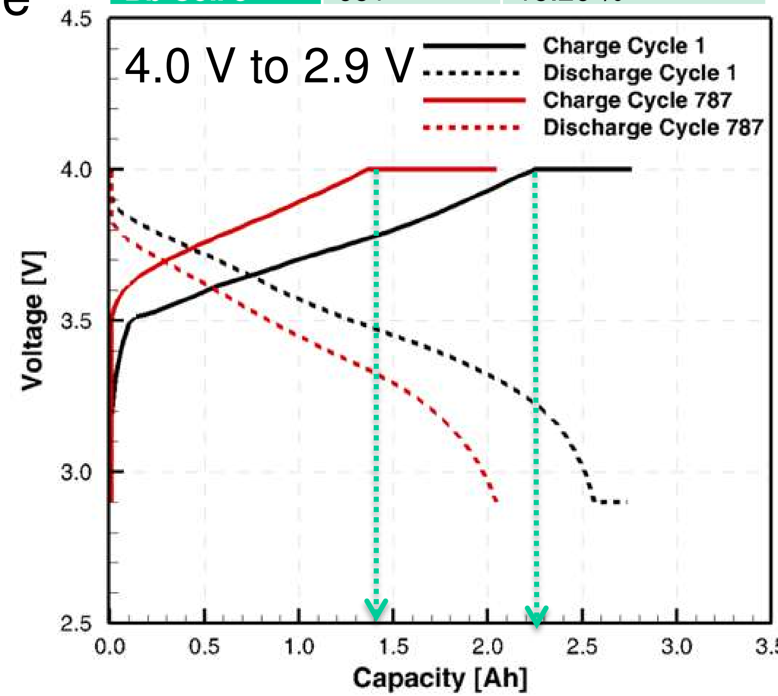


Cell ID	Number of Cycles	Capacity Fade
Bb Cell 1	787	25.30 %
Bb Cell 2	785	25.29 %
Bb Cell 7	800	23.87 %
Bb Cell 8	640	20.11 %
Bb Cell 9	648	20.09 %
Bb Cell 10	616	15.65 %
Bb Cell 4	647	15.50 %
Bb Cell 6	324	15.44 %
Bb Cell 3	651	15.26 %

With age, the same voltage is reached faster during the charge step.

Cell ID	Number of Cycles	Capacity Fade
Ba Cell 2	319	26.70 %
Ba Cell 1	300	24.23 %
Ba Cell 6	221	23.79 %
Ba Cell 5	222	22.97 %
Ba Cell 4	234	18.74 %
Ba Cell 8	201	16.21 %
Ba Cell 10	269	15.49 %
Ba Cell 3	201	15.41 %

Does the Charger recognize aging?



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Recommendations for Chargers / Charging Infrastructure

Charger / Charging Infrastructure

- Battery should be independently fault-tolerant
- Charger should recognize battery specification and provide relevant protocols for charge and discharge (use of EEPROM)
- End of discharge voltages if the charger also carries out maintenance cycles
- Reset of over-discharged battery should not be automatic
- Fire Extinguishing Methods
- Health Check on battery
- Cutoff charge current as soon as charging is complete
- Take aging effects into account
- Protective controls with monitoring cell and battery voltage, current and temperature
- Cell balancing
- Protected against current backflow from battery into charger

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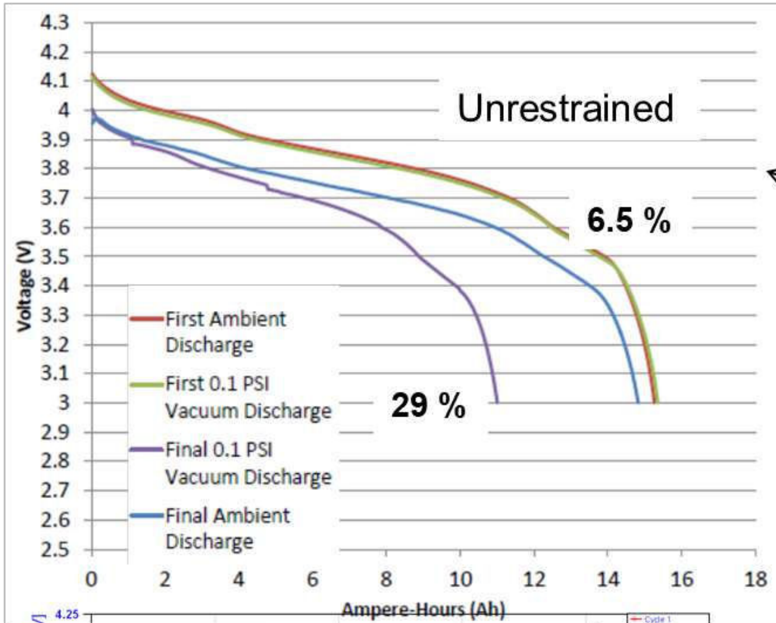
Environmental Challenges: Altitude Testing

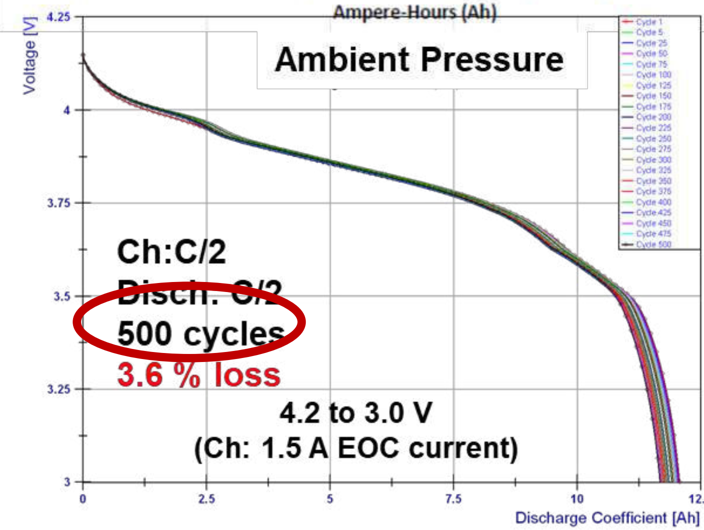


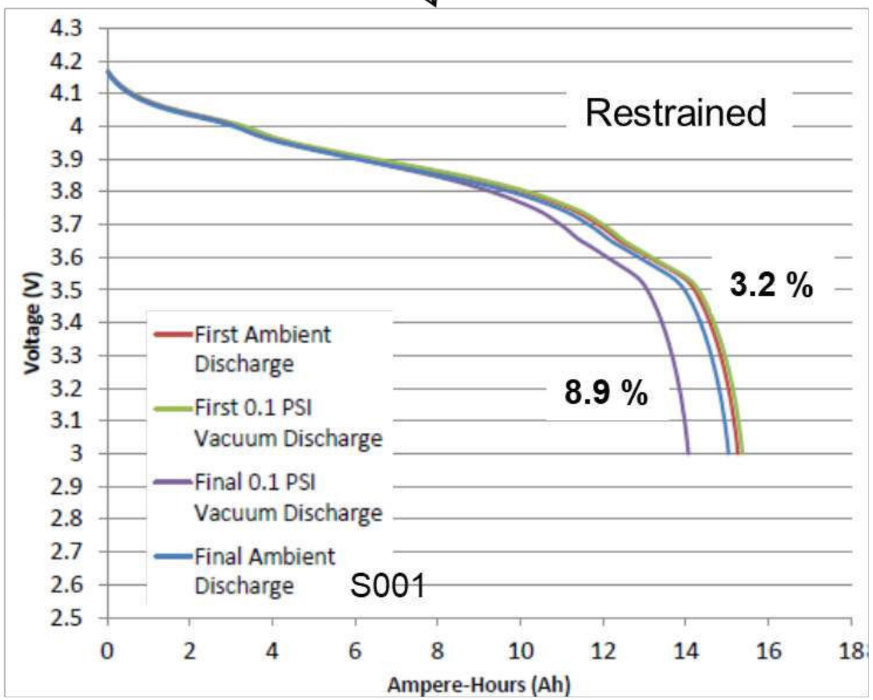
15 Ah Pouch Cell

Cells show loss in capacity when cycled under vacuum conditions

Vacuum : 30 cycles

C/2 Charge and Discharge





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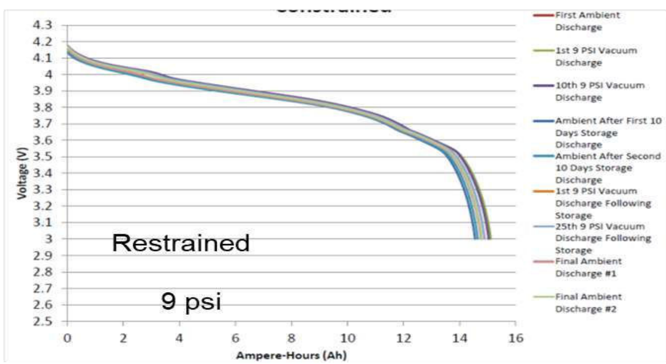
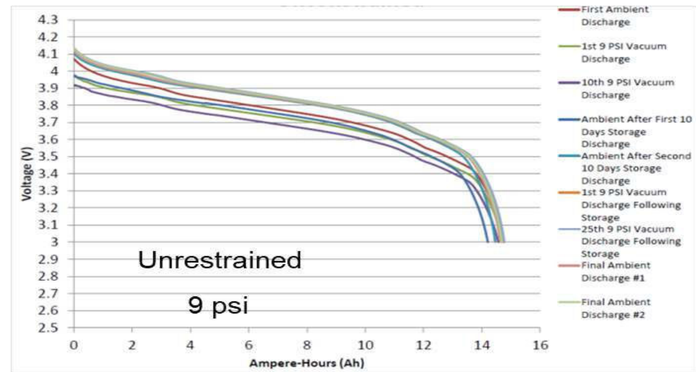
High Altitude Testing

Pouch format cells from different manufacturers behave differently at lower pressure environments.

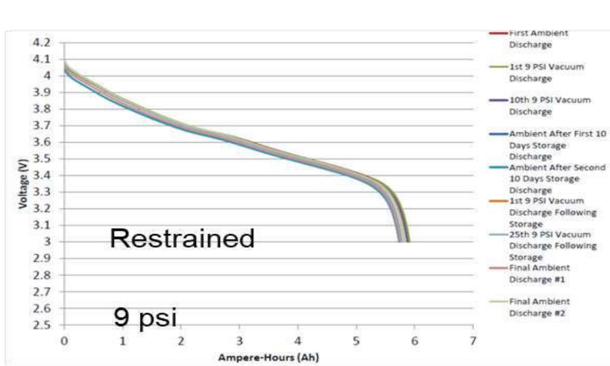
Restraints are required for all pouch format cell

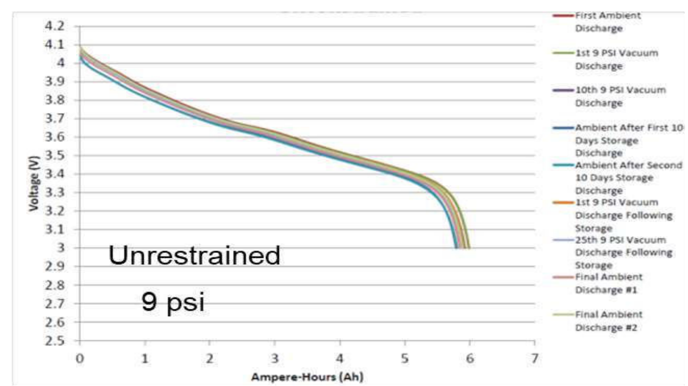
15 Ah Pouch Cell (Manufacturer A)



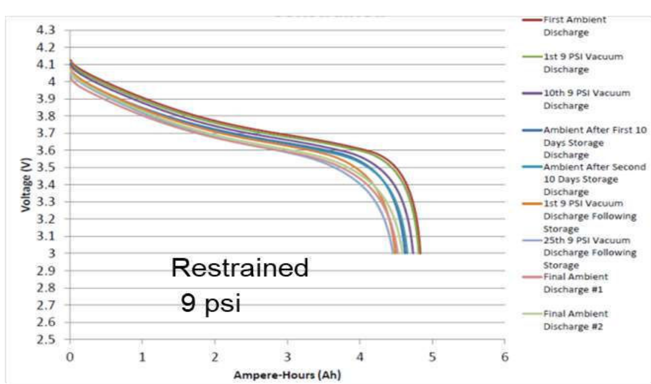


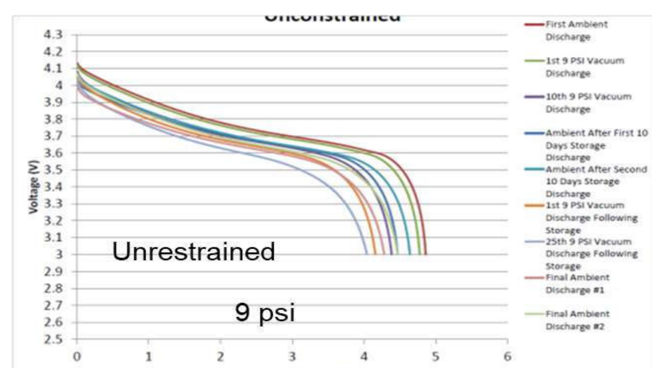
6 Ah Pouch Cell (Manufacturer B)



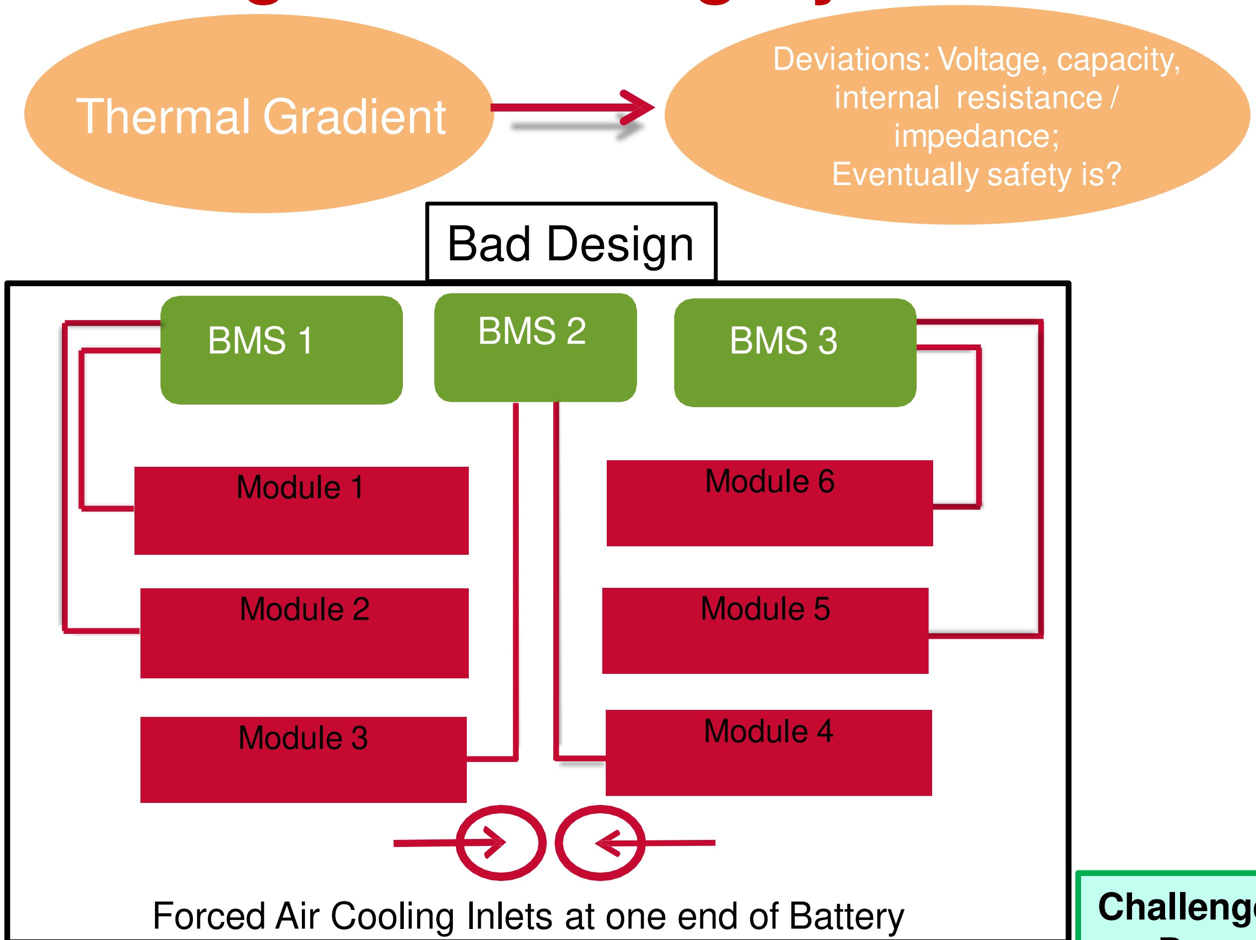


5 Ah Pouch Cell (Manufacturer C)

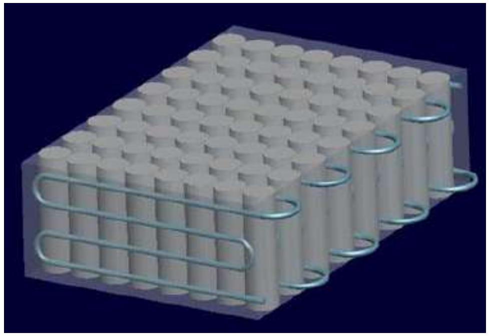




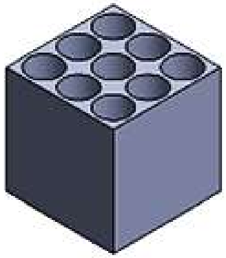
Challenges with Battery Designs for EVs– Heating and Cooling Systems



Active Cooling System



Passive Cooling System



Challenges:
- **Leakage of liquid cooling systems**
- **Inefficient cooling**

Challenges of Heating Systems:
- **Dependent on battery power to turn on**
- **Providing uncontrollable heat**

Cooling design that provides the smallest possible thermal gradient in the battery should be chosen

Other Challenges

High Voltage Safety

Complexity of Sensing Systems / BMS

<u>Quality and relevancy</u> of Sensors, electronics, protective devices, software

Flammability and Off-gassing

Fire Extinguishing Methods

Transportation Safety

Toxicity

Environmental Pollution

Stranded Energy

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Summary and Recommendations

- Design and use **within cell/battery manufacturer's spec for voltage, current and temperature**

OR

- **Qualify with ample margin** to requirements for application
- Batteries should be **independently fault-tolerant** unless they are embedded into the hardware and cannot be user-replaced.
- Faulty design, use or misuse need not lead to immediate catastrophic failures, it is usually a **cumulative effect** that results in a **sudden catastrophic event.**
- **Reducing voltage range** (less than manufacturer's recommended voltage range) used by application increases battery life, health and safety
- **Complete characterization of performance and safety** of lithium-ion cells and batteries should be carried out by testing (stringent qualification of design).
- **Testing stringently in the appropriate configuration and relevant environment** is required for baseline characterization.
- Being **vigilant of off-nominal behavior and recognizing** this during the life of the battery is a critical part of removing defective cells/batteries from service before they go into a catastrophic failure mode. More important for long term usage batteries.
- Lastly, **usage limits (manufacturer's spec), appropriate monitoring and control, balancing and thermal design** are key to prevent subtle defects from turning into nucleation sites for larger fault conditions.

Design conservatively and test stringently……

Acknowledgment

UL Team:

Saad Azam

Kanarindhana Kathirvel

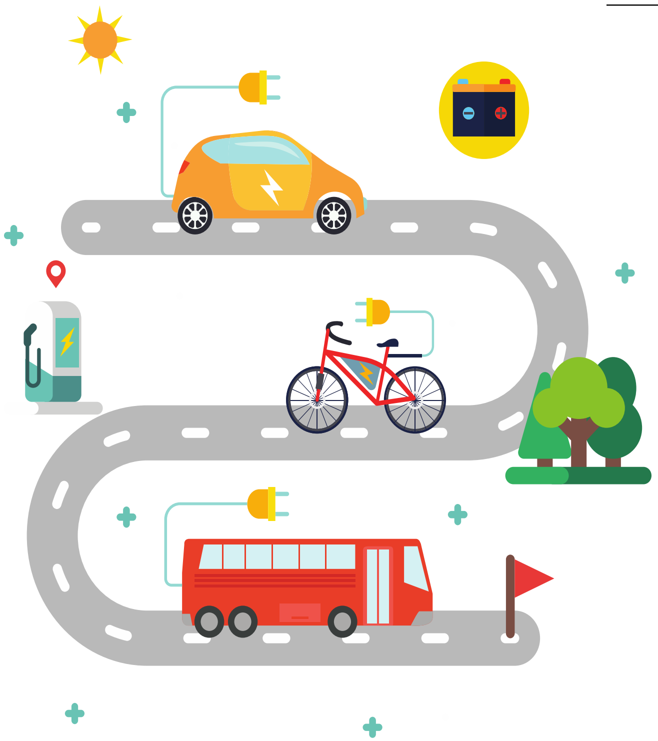
Tapesh Joshi

Daniel Juarez- Robles

ELECTRIC MOBILITY FORUM

ENGAGE

Connecting Big Ideas To Action



Lithium-ion Battery Hazards and Design Challenges for the Electric Vehicle Sector

May 25, 2020
7:00 PM - 8:00 PM (IST)
WRI India Delhi

Speaker:
Dr. Judy Jeevarajan
Research Director – Battery Safety, Underwriters Laboratories Inc.

Moderator:
Shravani Sharma
WRI India

WRI INDIA — ROSS CENTER

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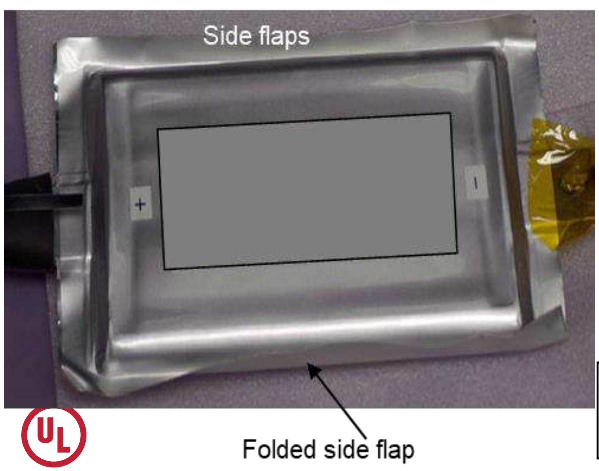
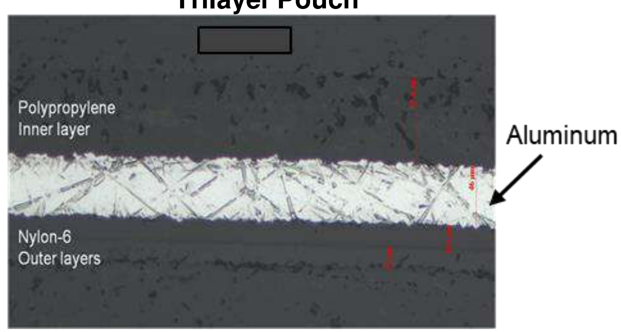
Additional Information

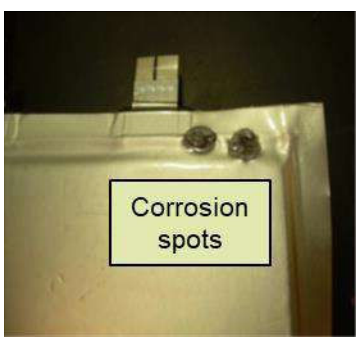
Considerations for Pouch Format Cells

- Lithium-ion pouch format cells have become significantly prevalent today due to the lower cost and complexity of manufacturing.
- In a lithium-ion pouch cell design, the enclosure (pouch) is made up of a trilayer material which consists of Aluminum sandwiched between two layers of polymer or plastic, also caused Aluminized plastic. During the cell manufacturing process, the molding process can cause the corners of the pouch to stretch and crack. Pinholes can also be observed in other parts of the pouch on the internal plastic layer during the handling process.
- Lithium-ion cells in the pouch format are still li-ion types with a liquid electrolyte. Although referred to commonly as polymer cells, they do not have a polymer electrolyte. Some pouch type cells have a higher polymeric composition in the cathode and anode. However they still need liquid electrolyte in order to function.
- The pouch format cells require restraints on the flat sides that will prevent swelling of the pouch. The first versions of the pouch cells (in early 2000s) displayed swelling while in storage and at low pressures and vacuum conditions. It is imperative to place restraints on the flat faces of the pouch cell design to prevent swelling of any kind. The pressure required for restraint should be obtained from the cell manufacturer.
- Pouch cell designs are typically designed to have one of the tabs burn off under a short circuit condition thus preventing the internal cell stack from going into a catastrophic failure condition.



Trilayer Pouch





Courtesy: E. Darcy, AABC 2012

Considerations for Pouch Format Cells

Through the growth of the pouch format cell industry, several characteristics have been observed that one needs to be aware of. They are the following:

- Pouch cells are typically not designed with cell-level safety controls.
  - A very few cell manufacturers place a smart circuit board with overvoltage, undervoltage and overcurrent controls that is physically located between the terminals of the pouch but provide cell-level monitoring and control for each cell.
- The terminal tabs on the pouch cell need to be reinforced to prevent tearing or cracking or tab breakage at the point where the tab extends from the pouch.
- Swelling of pouch can occur during storage periods.
- Swelling of pouch can occur under extreme thermal environments.
- Swelling of pouch occurs under vacuum (space environments) or low pressure (high altitude as for UAVs) conditions.
- Swelling of pouch and breakage of pouch seal under off-nominal conditions such as overcharge, overdischarge, external and internal shorts, high temperatures, etc.
- Corrosion of pouch – when pin holes develop in the internal polymeric layer, the electrolyte corrodes the aluminum layer of the pouch causing a weakening of the pouch.
- Flexibility and softness of the pouch makes it easy to dent or deform the pouch. This can cause electrodes to touch each other in the corners or even internal shorts to be created in any part of the cell that has undergone deformation or denting.
- Pouch format cells sometimes have side flaps that are the heat-sealed areas. These flaps are oftentimes folded over by the battery manufacturer which causes stress on the corners and sides leading to cracks and holes created in the inner layer of the pouch.
- Pouch cells should be tested as single cells, under all off-nominal conditions listed on Pages 40 and 41 (Safety Test Protocols – Cell). The test should be carried out using the configuration (with or without restraints) found in the relevant application they are to be used in. The results of the tests will provide data on the limitations of the cell under various off-nominal conditions as most pouch cells do not have internal safety controls, the nature of failure including the location on the pouch where venting of the cell occurs (highly dependent on the cell design).
- Pouch cells can display a bigger fire under an off-nominal event compared to a metal can cell, as the pouch seal opens at low pressures (e.g. ~ 50 psi) that causes the release of hot electrolyte gases and vapors that combust when they fall on the hot cell surface. The fire will burn until all the electrolyte in the cell is used up.

Energy and Toxicity

Two main factors that categorize safety:

- Energy provided in Wh/kg or Wh/L
- Toxicity – based on electrolyte (vapors, decomposition products, etc.)

Toxicity:

- **KOH:** alkaline, NiCd, NiMH, AgZn – caustic and corrosive- will burn skin and eyes.
- **H_2SO_4:** Lead acid- acidic and corrosive, will create acid fumes that can damage throat and lungs.
- **$SOCl_2$:** $LiSOCl_2$ and BCX- burn skin, eyes, damage throat and lungs to a higher degree than above and can be lethal.
- $Li(CF)_x$ and $LiMnO_2$, **Li-ion**: affects skin and eyes on contact; electrolyte is flammable and can cause fire in the presence of an ignition source.

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EV Battery Performance Tests and Standards

I. IEC 62260-1:2010: Secondary lithium-ion cells for the propulsion of electric road vehicles;

II. IEC 61982:2012: Secondary batteries (except lithium) for the propulsion of electric road vehicles - Performance and endurance tests

III. ISO 12405-4:2018: Electrically propelled road vehicles -- Test specification for lithium-ion traction battery packs and systems -- Part 4: Performance testing;

IV. DOE-INL/EXT-15-34184: Battery test manual for electric vehicles;

V. DOE-INL/EXT-07-12536: Battery test manual for plug-in electric vehicles;

VI. SAE 2288 Life Cycle Testing of Electric Vehicle Battery Modules;

VII. SAE J1798:2008: Recommended Practice for Performance Rating of Electric Vehicle Battery Modules.

VIII. NFPA 855 Fire Codes and Standards

ARAI Standards for EV Batteries

AIS-037/2004 & Amd. No. 1 to 9	Battery Operated Vehicles –Requirements for Construction and Functional Safety
AIS-038 (Rev.1):2015 and Amd.1	Electric Power Train Vehicles- Construction and Functional Safety Requirements
AIS-039	Battery Operated Vehicles – Measurement of Electrical Energy Consumption
AIS-039 (Rev.1) & Corri. 1	Electric Power Train Vehicles– Measurement of Electrical Energy Consumption
AIS-040 (Rev.1):2015 and Amd.1	Electric Power Train Vehicles - Method of Measuring the Range
AIS-040	Battery Operated Vehicles – Method of Measuring the Range
AIS-041	Battery Operated Vehicles –Measurement of Net Power and the Maximum 30 Minute Power and speed
AIS-041 (Rev.1):2015	Electric Power Train Vehicles Measurement of Net Power and The Maximum 30 Minute Power
AIS-048 & Amd. 1 and Amd 2	Battery Operated Vehicles - Safety Requirements of Traction Batteries
AIS-049 and Amd. 1 & 2	Battery Operated Vehicles - CMVR Type Approval for Battery Operated Vehicles
AIS-049 (Rev. 1): 2016	Electric Power Train Vehicles - CMVR Type Approval for Electric Power Train Vehicles

Mechanical Abuse Tests

*ARAI (AIS-048) test descriptions

I. **Mechanical shock**
   - Module level with peak acceleration of 30 g for 15 ms duration at 100% SOC

II. **Drop**

III. **Penetration**
   - Cell and Module level (3 cells or 100 mm depth of penetration)

IV. **Immersion**

V. **Crush/crash**

VI. **Rollover**
   - Module level at 360˚/min (continuous)

VII. **Vibration**
   - Module level with sine wave at 30-150 Hz frequency at 100% SOC

Electrical Abuse Tests

*ARAI (AIS-048) test descriptions

I. **External short circuit**
   - Cell, module, and pack levels at 100% SOC with <5 mΩ resistance

II. **Internal short circuit**

III. **Overcharge/overdischarge**
   - Cell, module, and pack levels at 100% SOC at C/10 for 10 hours
   - No overdischarge test

Environmental Abuse Tests

I. Thermal stability
II. Thermal shock and cycling
III. Overheat
IV. Extreme cold temperature
V. Fire

*No environmental abuse tests are specified under ARAI (AIS-048) standard