Requirements and Approaches for Li-Ion Batteries regarding Vehicle Safety

Rainer Justen, Daimler AG, 2017-01-31

Advanced Automotive Battery Conference Europe
Mainz, Germany
1. Mercedes-Benz Hybrid and Electric Vehicles
2. Battery Types and Challenges for Crash Safety
3. Legal Requirements and Safety Standards
4. Safety Concepts
**Battery Types**

### Hybrid
- **Dimension [mm]**: 450x180x150
- **Weight / Volume**: 23 kg / 12 Liter
- **Cell Capacity (nominal)**: 6,5Ah
- **Cell Count**: 35
- **Cell Format**: VL6P-round
- **Energy@1C**: 0,8 kWh
- **Voltage**: 143V
- **Peak Power**: 22 kW
- **Life Time**: 10y / 300,000 micro cycles

### Plug-In Hybrid
- **Dimension [mm]**: 905x525x200
- **Weight / Volume**: 114 kg / 82 Liter
- **Cell Capacity (nominal)**: 22,5 Ah
- **Cell Count**: 120
- **Cell Format**: PHEV 1
- **Energy@1C**: 8712 Wh (106Wh/l)
- **Voltage**: 240V to 432V
- **Peak Power**: > 90 kW
- **Continuous Power**: 40 kW
- **Life Time**: 10y / 300,000km

### Electric
- **Dimension [mm]**: 1000x475x200
- **Weight / Volume**: 175kg / 90 Liter
- **Cell Capacity (nominal)**: 50Ah
- **Cell Count**: 93
- **Cell Format**: HEA-50
- **Energy@1C**: 17,6 kWh
- **Voltage**: 391V
- **Peak Power**: 75 kW
- **Continuous Power**: 55 kW
- **Life Time**: 10y / 300,000km

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Challenges for Crash Safety of Electric Vehicles by Media View

U.S. opening formal probe into GM Volt fire risk

Dutchman dies in Tesla crash; firefighters feared electrocution

Regulators Examine Electric Car Batteries After Fire

Three BYD e6 Passengers Killed in Fiery Crash, Spurring EV Safety Concern

Lithium-ion batteries are popular in plug-in cars.
Causation of Battery Fires in Electric Vehicles

Accidents
- Overrun of objects on street
- Charging
- Electrical defects

Reasons from 7 known fire incidents with Tesla Model S

<table>
<thead>
<tr>
<th>Causation</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidents</td>
<td>3 (all very severe Pole Impacts, 2 with fatal injuries)</td>
</tr>
<tr>
<td>Objects</td>
<td>2</td>
</tr>
<tr>
<td>Charging</td>
<td>1</td>
</tr>
<tr>
<td>Electric defect</td>
<td>1</td>
</tr>
</tbody>
</table>
VICTIMS IN FIERY TESLA CRASH IDENTIFIED; OFFICIALS SAY SEVERAL INTENSE FIRES DELAYED RESCUE EFFORT

Posted 2:38 am, November 3, 2016, by CBS4 Web and Alexis McAdams,
Updated at 03:55pm, November 3, 2016

INDIANAPOLIS, Ind. – A series of intense fires both large and small prevented rescue crews from reaching the victims of a fiery car crash near downtown Indianapolis early Thursday morning.

According to Kevin Jones with the Indianapolis Fire Department, firefighters couldn’t reach the victims immediately because of several fires. They had to contend with the main fire centered on the Tesla itself as well as several smaller fires from the lithium ion batteries that power the car. Jones said some of those battery cells fired off “almost like projectiles” while crews tried to get the situation under control.

“Lithium ion batteries burn very hot,” Jones said Thursday afternoon. “To extinguish that type of fire with those batteries involved, it’s necessary to apply copious amounts of water.”

Jones said IFD has responded to crashes involving electric and hybrid vehicles before, but nothing matching the magnitude of Thursday’s “significant crash,” which left debris in all different directions. Jones said crews estimated they took five to ten minutes to extinguish the flames.

Jones said Tesla, like many manufacturers, provides and emergency response guide. In most cases, the company recommends that crews let fires burn themselves out. However, given the fact people were inside the car, Jones said that wasn’t possible in this situation.

“That is not an option,” Jones said. “The batteries can burn for up to 24 hours.”

He reiterated that crews had to use large amounts of water to get the fires under control, delaying their efforts to reach the driver and passenger. Rescue crews concentrated their rescue efforts on the passenger because the driver had been declared dead at the scene.
Early Safety Test Standards derived from Consumer Applications

**Safety and Misuse Tests (SAND 2005-3123*)**

**Mechanical Abuse Test**
- Controlled Crush (15%/50%)
- Penetration (Nail)
- Drop Test
- Immersion
- Roll Over Simulation
- Mechanical Shock

**Thermal Abuse Tests**
- Thermal Stability Test
- Simulated Fuel Fire
- Elevated Temperature Storage
- Rapid Charge/Discharge
- Thermal Shock Cycling

**Electrical Abuse Tests**
- Overcharge/Overvoltage
- Short Circuit
- Overdischarge/Voltage Reversal
- Partial Short Circuit Test

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**Controlled Crush**

Module compressed between 2 countertops, one with a specific profile, the other plane.

Device under test to be positioned according to the most critical loading and penetration.

The test will be done in two steps:

1.) After 15% deformation of the module height, the static load will be maintained for 5 minutes.

2.) Further deformation, either up to 50% of module height, or to a max. force of 1000 G of the module mass.

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**Penetration (Nail)**

Penetration of the module with a conductive steel bar which is electrically isolated from the module with a penetration velocity of 8 cm/s.

In case of a singular cell, the diameter of the bar is 3mm, and the cell must be completely penetrated.

Testing a module or pack, the diameter is 20 mm, and either 3 cells / units must be penetrated, or the penetration depth must be 100 mm.

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**Drop Test**

Module drops from a height according to the equivalent deformation energy (max. 10 m) on a steel cylinder of a diameter of 300 mm.

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*Figure 2. Drop test impact.*
Correlation of Previous Test Standards with Automotive Demands

- Test standards predominantly feasible for cells and modules only.
- Now correlation with the loads applied to batteries in real world accidents.
- No correlation of loads with in-vehicle battery weight.
- Hazard-Level assessment not appropriate for automotive applications.

### Hazard Level Classification Criteria & Effect

<table>
<thead>
<tr>
<th>Hazard Level</th>
<th>Classification Criteria &amp; Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 0</td>
<td>No Effect</td>
</tr>
<tr>
<td>Level 1</td>
<td>Passive protection activated</td>
</tr>
<tr>
<td>Level 2</td>
<td>Defect/Damage</td>
</tr>
<tr>
<td>Level 3</td>
<td>Leakage, $\Delta$ mass &lt; 50% of electrolyte weight</td>
</tr>
<tr>
<td>Level 4</td>
<td>Venting, $\Delta$ mass &gt; 50% of electrolyte weight</td>
</tr>
<tr>
<td>Level 5</td>
<td>Fire or flame</td>
</tr>
<tr>
<td>Level 6</td>
<td>Rupture</td>
</tr>
<tr>
<td>Level 7</td>
<td>Explosion</td>
</tr>
</tbody>
</table>

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## Enhancements of Battery Test Standards for Automotive Applications

<table>
<thead>
<tr>
<th>Norm</th>
<th>SAE J2464*</th>
<th>SAE J2929</th>
<th>ISO 12405-3</th>
<th>ECE R100-2</th>
<th>GB/T 31467.3-2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter</td>
<td>4.3.6. Crush Test (cell level or above)</td>
<td>4.6 Battery Enclosure Integrity</td>
<td>9.2. Contact force at vehicle crash</td>
<td>6.4.2 Mechanical Integrity</td>
<td>7.6 Crush</td>
</tr>
<tr>
<td>Test piece</td>
<td>Ø 150</td>
<td>as SAE J2464</td>
<td>as SAE J2464</td>
<td><em>Based on USABC/SANDIA</em></td>
<td></td>
</tr>
<tr>
<td><strong>Test load</strong></td>
<td>15% / 50% Compression, max. 1000-times of battery weight</td>
<td>100 kN</td>
<td>100 kN</td>
<td>100 kN</td>
<td>200 kN in x and y axis</td>
</tr>
</tbody>
</table>
| Requirements | No requirements | • No Enclosure cracks  
• No Fire  
• No Explosion  
• Isolation > 100 Ω/V | • No Enclosure cracks  
• No Fire  
• No Explosion  
• No Electrolyte leakage | • No Fire  
• No Explosion  
• Electrolyte-leakage < 7%, max. 5 l  
• Isolation > 100 Ω/V | • No Fire  
• No Explosion |
| Optional fulfillment | - | 4.6.1 Load according to crash simulation  
4.6.3 Vehicle crash | 9.2.3b Vehicle crash | 8D Load according to crash simulation  
6.4.2.1 Vehicle crash | |

*Based on USABC/SANDIA*
### Legal Crash Requirements for Electric and Hybrid Vehicles (Post Crash)

<table>
<thead>
<tr>
<th>Market</th>
<th>Regulation</th>
<th>Crash Tests</th>
<th>Rechargeable Energy Storages (RESS)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECE</td>
<td>ECE R94/95/12</td>
<td>Frontal: 40% ODB, 56 km/h&lt;br&gt;Side: 90° MDB, 50 km/h</td>
<td>• The RESS shall stay in their original locations with their components inside and no intrusion into the passenger compartment is allowed&lt;br&gt;• No electrolyte spillage into passenger compartment within 30 min after impact (outside no more than 7% or max. 5 l)&lt;br&gt;• No explosion or fire of RESS</td>
</tr>
<tr>
<td>USA</td>
<td>FMVSS 305</td>
<td>Frontal: 0/30°, 48 km/h&lt;br&gt;Side: 27°-MDB, 54 km/h&lt;br&gt;Rear: 70% MDB, 80 km/h</td>
<td>• No electrolyte spillage in passenger compartment (Outside passenger compartment &lt; 5 l)&lt;br&gt;• RESS must remain on vehicle</td>
</tr>
<tr>
<td>Japan</td>
<td>TRIAS 17(2)–J111(2)–02 (TRIAS 67-3)</td>
<td>Frontal: 0°, 50 km/h&lt;br&gt;40% ODB, 56 km/h&lt;br&gt;Side: 90° MDB, 50 km/h&lt;br&gt;Rear: 180°, 50 km/h</td>
<td>• No electrolyte spillage in passenger compartment (basically &lt; 7 %)&lt;br&gt;• The RESS shall remain in their mounting points</td>
</tr>
<tr>
<td>China</td>
<td>GB/T 31498-2015</td>
<td>Frontal: 0°, 48 km/h&lt;br&gt;40% ODB, 56 km/h&lt;br&gt;Side: 90° MDB, 50 km/h</td>
<td>• No electrolyte spillage in passenger compartment (Outside passenger compartment &lt; 5 l)&lt;br&gt;• RESS shall be retained at its installation location&lt;br&gt;• RESS shall not enter the passenger compartment&lt;br&gt;• No explosion or fire of RESS</td>
</tr>
<tr>
<td>Korea</td>
<td>KMOVSS Art 91 Test Proc. 47</td>
<td>Frontal: 0°, 48 km/h&lt;br&gt;Side: 90° rigid, 32 km/h&lt;br&gt;Rear: 180° rigid, 48 km/h</td>
<td>• RESS must remain on vehicle&lt;br&gt;• No electrolyte spillage in passenger compartment (Outside passenger compartment &lt; 5 l)&lt;br&gt;• No explosion or fire of RESS&lt;br&gt;• No endangerment by movement of RESS</td>
</tr>
</tbody>
</table>
Mechanical Integrity Test for Battery Crash Evaluation (ECE R100-2)

**Validity**
- Verification Test
- Requirements

**Component approval**
(no further crash verification required)

**Battery System-Level Evaluation**
- Load: 100 kN
- Battery

**Vehicle approval only**

**Vehicle-Level Evaluation**
- Front Crash
- Side Crash
- Rear Crash

**Requirements**
- No rupture of battery enclosure according to IPXXB (Finger proof)
- No electrolyte leakage out of battery housing
- No venting, No fire
## Damage Mechanisms of HV-Batteries During Crash

<table>
<thead>
<tr>
<th>Damage pattern</th>
<th>Possible safety related effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damages with battery enclosure opening</td>
<td>Electric shock during contact w/ interior high voltage elements</td>
</tr>
<tr>
<td>Mechanical cell deformations</td>
<td>Electrolyte leaking, venting, ignition (spontaneous)</td>
</tr>
<tr>
<td>Internal cell short circuits due to mechanical deformation</td>
<td>Temperature increase with degassing, fire (spontaneous)</td>
</tr>
<tr>
<td>Electric arcs due to short circuits of electric conducts / circuit board</td>
<td>Ignition, fire (spontaneous)</td>
</tr>
<tr>
<td>Leakage in cooling system</td>
<td>Progression of short circuits and temperature increase (delayed)</td>
</tr>
</tbody>
</table>
Safe Integration of Energy Storages

Standard crash tests will cover approx. 90% of all vehicle deformations in real life accidents.
### Assessment Criteria of HV-Batteries

#### Vehicle Crash Tests
- No Explosion
- No Fire
- No Lost of isolation
- No Electrolyte leakage
- No Enclosure opening (IPXXB)
- No Electric arcs
- No Enclosure cracks
- No Damages on Modules/Cells/Electronics
- No leakage of battery cooling system

#### Component Due Care Evaluation
- No Explosion
- No Fire
- No Lost of isolation
- No Electrolyte leakage
- No Enclosure opening (IPXXB)
- No Electric arcs

### Least possible loads on battery

- Least possible loads on battery

### Avoiding thermal incidents

- Avoiding thermal incidents

Covered by GB/T and ECE
Summary

- Previous test standards for battery safety are derived from consumer applications and were not appropriate for automotive traction batteries
- Current enhancements of battery test standards are more realistic for load cases in vehicle accidents
- Safety assessment must be conducted on a complete battery system level
- Crash safety of automotive traction batteries is a best possible combination of vehicle integration and a mechanical inherent stability of the battery
Thank You for Your Attention!

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