Outline

1. Lithium-ion batteries
2. Safety tests and -requirements
3. Crash safety
4. Transport safety
Safety of Li-Ion Batteries

Battery fire on consumer products

Battery fire on planes

Battery fire on Hybrid- and Electric Vehicles
Safety during handling with Li-Ion Batteries
Critical media coverage at safety of HV-batteries
Crash Case Chevrolet Volt (5/2011)

- Mechanical damages to the battery and cooling system may result in short circuits and uncontrolled discharge current or chemical reactions with the possible result of overheating and fire.
## Li-ion Batteries in Mercedes-Benz Vehicles

<table>
<thead>
<tr>
<th><strong>Hybrid (HEV)</strong></th>
<th><strong>Fuel Cell Vehicles (FCEV)</strong></th>
<th><strong>Plug-In-Hybrid (PHEV)</strong></th>
<th><strong>Battery Electric Vehicles (BEV)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>E-class S-class</td>
<td>B-class</td>
<td>S-class</td>
<td>A-class smart SLS</td>
</tr>
<tr>
<td>Round cell</td>
<td>Round cell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23 kg</td>
<td>47 kg</td>
<td></td>
<td>178 kg</td>
</tr>
<tr>
<td>140 V</td>
<td>246 V</td>
<td></td>
<td>390 V</td>
</tr>
<tr>
<td>800 Wh</td>
<td>1,4 kWh</td>
<td></td>
<td>18 kWh</td>
</tr>
<tr>
<td>20 kW</td>
<td>30 kW</td>
<td></td>
<td>55 kW</td>
</tr>
</tbody>
</table>

**Performance batteries**

**Energy batteries**
Oncoming market launches up to 2014

- **S-class Hybrid**
- **C-class Hybrid** (Successor)
- **M-class Hybrid**
- **S-class Plug-In Hybrid**
- **C-class Plug-In Hybrid** (Successor)
- **B-class E-Cell**
- **SLS E-Cell**
Construction of Lithium-Ion Battery System

**Cell chemistry**

- **Anode:** Grafite, Carbon, LTO Li-Titanate
- **Cathode:** LCO Li-Cobalt-Oxide, LNO Li-Nickel-Oxide, LMO Li-Manganese-Oxide, NMC Li-Ni-Manganese-Cobalt, NCA Li-Ni-Cobalt-Aluminium, LFP Li-Fe-Phosphate

**Cell form**

- **Round Cell**
- **Prismatic Cell**
- **Pouch Cell**

**Battery system**

- **Cell**
- **Module**
- **Pack**
- **Battery Electronics**
Construction of Lithium-Ion Battery System
### Specific characteristics of Li-ion Batteries regarding Safety

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>High weight (25 to &gt; 400 kg)</td>
<td>![Warning]</td>
</tr>
<tr>
<td>Cells are not disengageable (Voltage &gt; 50 V also by empty batteries)</td>
<td>![Warning]</td>
</tr>
<tr>
<td>Li-ion Batteries consists of inflammable electrolytes (Significant difference to NiMH, NiCd und Pb- accumulators)</td>
<td>![Warning]</td>
</tr>
<tr>
<td>In case of damage risk of internal short-circuit in cells with self-heating and fire (Thermal Runaway)</td>
<td>![Warning]</td>
</tr>
<tr>
<td>Emergent electrolyte is strong corrosive</td>
<td>![Warning]</td>
</tr>
</tbody>
</table>
Operation area of Li-Ion Battery Systems

Over-discharge < 2 V can result in safety problems at the next charge \(\Rightarrow\) formation of dendrites (internal short-circuit)

Overcharge > 4.5 V directly results in safety problems \(\Rightarrow\) Decomposition process with exothermic reactions, Thermal Runaway

Charging Voltage must be controlled exactly!
Safety Devices for Batteries/Cells

**Shut-down / ceramic separators**
- Fusing of separator w/ lost of porosity at 130°C (current interruption)
- Stability at >> temperatures

**Pressure Relief Valve, Burst Disk**
- Pressure release w/o current interruption
- Pressure release w/ current interruption

**Charge Interrupting Device (CID)**
- Current interruption in EX-Atmosphere or internal (controlled) short-circuit

**Positive Temperature Coefficient (PTC)**
- Current limitation by PTC materials
  - At present only in Consumer/18650 cells

**External Impact**
- Fuse, Thermo Switch
  - Cut off HV-battery

**Switch, Relay**
- Cut off HV-battery
Test types of Batteries

1. Safety Tests
2. Misuse Tests
3. Transport Tests
4. Environment Tests
5. Performance and Reliability Tests
6. Lifecycle Tests
Safety Relevant Battery Test Standards

Safety and Misuse Tests*

**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

Transport Tests (UN38.3)

T1: Altitude simulation
T2: Thermal Test
T3: Vibration
T4: Shock
T5: External short circuit
T6: Impact
T7: Overcharge
T8: Forced Discharge


Execution of tests on a.) cell level b.) modul level c.) pack level
Mechanical Abuse Tests (according SAND 2005-3123)

Controlled Crush

Module will be crushed between structures and flat plate
Test has to be conducted in 2 stages:
1.) Compression up to 15% of module height, 5 min holding time
2.) Deformation up to 50% of module height, or a maximum load equivalent 1000 times of battery weight.

Penetration (Nail)

Penetration with an isolated steel bar velocity: 8 cm/s
Bar diameter of 3 mm for a single cell. Object must be penetrated completely
Bar diameter of 20 mm for modules or packs. Penetration of at least 3 cells (unit) or a minimum of 100 mm is required.

Drop Test

Free fall from 10 meter high towards a steel cylinder of 150 mm radius

Figure 1. Crush test on module surface.

Figure 2. Drop test impact.
Safety and Misuse Tests

Mechanical Abuse Test
- Controlled Crush (15%/50%)
- Penetration
- Drop Test

- Existing test standards not close enough to reality regarding accident loads
- No correlation of load level to battery weight
- Execution of test standards mainly on cell level or module level feasible
- Evaluation of hazard levels too unspecific for automotive applications
## Legal Requirements for Hybrid and Electric Vehicles (Post Crash Extract)

<table>
<thead>
<tr>
<th>Market</th>
<th>Regulation</th>
<th>Rechargeable Energy Storages (RESS)*</th>
<th>High Voltage System*</th>
</tr>
</thead>
</table>
| ECE     | ECE R94/95/12 (in Revision)       | • The RESS shall stay in their original locations with their components inside and no intrusion into the passenger compartment is allowed  
• No electrolyte spillage into passenger compartment within 30 min after impact (outside no more than 7% or max. 5l)  
• No explosion or fire of RESS                                                   | Optional:  
• El. Isolation > 100/500 Ω/V d.c./a.c  
• High Voltage < 60 V in 5 sec  
• Electrical Energy < 0,2 J in 5 sec  
• Physical protection IPXXB                                                      |
| USA     | FMVSS 305                         | • No electrolyte spillage in passenger compartment (Outside passenger compartment < 5 l)  
• RESS must remain on vehicle                                                    | Optional:  
• El. Isolation > 100/500 Ω/V d.c./a.c  
• High Voltage < 60 V in 5 sec                                                   |
| Japan   | Art 17-2 Attachment 111           | • No electrolyte spillage in passenger compartment (basically < 7%)  
• The RESS shall remain in their mounting points                                | Optional:  
• Physical protection IPXXB (only Passenger Compartment)  
• El. Isolation > 100 Ω/V  
• High Voltage < 60 V in 5 sec                                                   |
| China   | GB/T 18384 GB/T 19751             | • RESS must remain on vehicle  
• No electrolyte spillage in passenger compartment (Outside passenger compartment < 5 l)  
• No explosion or fire of RESS  
• No endangerment by movement of RESS                                             | • No short circuit  
• Electrical isolation > 500 Ω/V (GB/T 19751, only for Hybrid)                 |
| Korea   | KMVSS Art 91 Test Proc. 47        | • RESS must remain on vehicle  
• No electrolyte spillage in passenger compartment (Outside passenger compartment < 5 l)  
• No explosion or fire of RESS  
• No endangerment by movement of RESS                                             | • El. Isolation > 100/500 Ω/V d.c./a.c                                           |

*Extract of relevant requirements
### Automotive related safety tests of LIB

(ECE R100 PART II: REQUIREMENTS OF A RECHARGEABLE ENERGY STORAGE SYSTEM (RESS) WITH REGARD TO ITS SAFETY)

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration</td>
<td>The purpose of this test is to verify the safety performance of the RESS under a vibration environment which the RESS will likely experience during the normal operation of the vehicle.</td>
</tr>
<tr>
<td>Thermal Shock and Cycling Test</td>
<td>The purpose of this test is to verify the resistance of the RESS to sudden changes in temperature. The RESS undergo a specified number of temperature cycles, which start at standard ambient temperature followed by high and low temperature cycling. It simulates a rapid environmental temperature change which a RESS will likely experience during its life.</td>
</tr>
<tr>
<td>Mechanical Shock</td>
<td>The purpose of this test is to verify the safety performance of the RESS under inertial loads which may occur during vehicle crash situation.</td>
</tr>
<tr>
<td>Mechanical Integrity</td>
<td>The purpose of this test is to verify the safety performance of the RESS under contact loads which may occur during vehicle crash situation.</td>
</tr>
<tr>
<td>Fire Resistance</td>
<td>The purpose of this test is to verify the resistance of the RESS, against exposure to fire from outside of the vehicle due to e.g. a fuel spill from a vehicle (either the vehicle itself or a nearby vehicle). This situation should leave the driver and passengers with enough time to evacuate and no re-ignition of fire should occur in a later stage.</td>
</tr>
<tr>
<td>External short circuit protection</td>
<td>The purpose of this test is to verify the performance of the short circuit protection. This functionality, if implemented, shall interrupt or limit the short circuit current to prevent the RESS from any further related severe events caused by short circuit current.</td>
</tr>
<tr>
<td>Overcharge protection</td>
<td>The purpose of this test is to verify the performance of the over-charge protection. This functionality, if implemented, shall interrupt or limit the charge current to prevent the RESS from any further related severe events caused by over-charge current and or voltage.</td>
</tr>
<tr>
<td>Over-discharge protection</td>
<td>The purpose of this test is to verify the performance of the over-discharge protection. This functionality, if implemented, shall interrupt or limit the discharge current to prevent the RESS from any further related severe events caused by over-discharge.</td>
</tr>
<tr>
<td>Over-temperature protection</td>
<td>The purpose of this test is to verify the function of the protection measures against internal overheating during the operation in the event of a single failure of the thermal control or cooling of the RESS.</td>
</tr>
</tbody>
</table>
Test Proposal for Battery Crash Evaluation
- Mechanical Integrity (ECE R100-2)

**Validity**
- Component approval
  (no further crash verification required)
- Battery System-Level Evaluation
  - Load: 100 kN
  - No rupture of battery enclosure according IPXXB (Finger proof)
  - No electrolyte leakage out of battery housing
  - No venting, No fire

**Requirements**
- Verification Test

**Vehicle approval only**
- Vehicle-Level Evaluation
  - Front Crash
  - Side Crash
  - Rear Crash
Safe integration of HV-batteries

Deformation areas in crash tests

Deformation probability in real life accidents*

Crash tests cover > 90% of all vehicle deformation in real life accidents

* Example: Vehicle type Station Wagon
Load Pattern of HV-Batteries in Vehicle Crash Tests

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>S 400 HYBRID</th>
<th>ML 450 HYBRID</th>
<th>B-class F-CELL</th>
<th>A-class E-CELL</th>
<th>Smart ED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>(Mild-) Hybrid (HEV)</td>
<td>(Full-) Hybrid (HEV)</td>
<td>Fuel Cell Veh. (FCEV)</td>
<td>Electric Veh. (BEV)</td>
<td>Electric Veh. (BEV)</td>
</tr>
<tr>
<td>Vehicle-Concept</td>
<td><img src="image" alt="S 400 HYBRID" /></td>
<td><img src="image" alt="ML 450 HYBRID" /></td>
<td><img src="image" alt="B-class F-CELL" /></td>
<td><img src="image" alt="A-class E-CELL" /></td>
<td><img src="image" alt="Smart ED" /></td>
</tr>
<tr>
<td>Battery Location</td>
<td>Engine Compartment</td>
<td>Rear Axle</td>
<td>Rear Axle</td>
<td>Underfloor</td>
<td>Underfloor</td>
</tr>
<tr>
<td>Relevant crash test</td>
<td><img src="image" alt="S 400 HYBRID" /></td>
<td><img src="image" alt="ML 450 HYBRID" /></td>
<td><img src="image" alt="B-class F-CELL" /></td>
<td><img src="image" alt="A-class E-CELL" /></td>
<td><img src="image" alt="Smart ED" /></td>
</tr>
</tbody>
</table>
Crush tests with HV-Batteries

Static

Dynamic

Type A: Battery moving

Type B: Battery fixed
Mechanical Crush Tests on Battery Pack Level

Examples for Batteries in Mercedes-Benz Vehicles:

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Mild-Hybrid (Li-Ion)</th>
<th>F-CELL (Li-ion)</th>
<th>Full-Hybrid (NiMH)</th>
<th>BEV (Li-ion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Data</td>
<td>370<em>230</em>205 mm</td>
<td>960<em>530</em>195 mm</td>
<td>930<em>570</em>195 mm</td>
<td>1025<em>490</em>235 mm</td>
</tr>
<tr>
<td></td>
<td>0,8 kWh, 24 kg</td>
<td>1,4 kWh, 48 kg</td>
<td>2,4 kWh, 83 kg</td>
<td>14 kWh, 148 kg</td>
</tr>
<tr>
<td>Deformation Pattern</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

- All mechanical loads ≥ 100 kN (static/dynamic)
- Battery deformation >> than in vehicle crashes

- No rupture of enclosure (IPXXB)
- No electrolyte leakage out of battery
- No venting
- No fire
Damage Mechanisms of HV-Batteries during Vehicle Accidents

External battery damages with enclosure openings
- Electric shock hazard due to high voltage contacts

Mechanical cell deformation
- Electrolyte leakage, Ignition

Internal cell short circuits as result of mechanical deformation
- Temperature rise, venting, fire (spontaneously)

Electric arcs from short circuits of electric conductors or boards
- Ignition, Fire (spontaneously)

Leakage in cooling system
- Short circuits resulting to temperature rise
Safety Over Range of HV-Batteries
Assessment Criteria of HV-Batteries

**Vehicle Crash Tests**
- No Explosion
- No Fire
- No Venting
- No Electric arcs
- No Lost of isolation
- No Enclosure opening (IPXXB)

**Component Due Care Evaluation**
- No Explosion
- No Fire
- No Venting
- No Electric arcs
- No Lost of isolation
- No Enclosure opening (IPXXB)
- No Enclosure cracks
- No Damages on Modules/Cells/Electronics
- No Electrolyte leakage
- No leakage of battery colling system
Crash Safety of Vehicle Traction Batteries

Battery stability
(Mechanical stability of battery enclosure)

Vehicle Integration
(Distance to crumble zone)

- No explosion
- No fire
- No venting
- No visible short-circuits
- Shock-proof protection

- Lowest load level as possible
- No critical damage of battery (Cell deformation, No leakage of electrolyte, cooling system)

Increasing Safety

- No explosion
- No fire
- No venting
- No visible short-circuits
- Shock-proof protection

- Very good
- Good
- Very low
- Low
Challenges of the Simulation of the Crash Performance of HV-Batteries

- In depth / realistic / detailed modeling of all battery components (Cell, Module, Electronics)
- Modeling of specific properties of battery technologies (Cell Chemistry)
- Validation of electrical properties
- Specific / analogous model of chemical properties (Thermal Runaway)

From Black Box View to Implicit Evaluation of Crash Response
Transport of Li-ion-Batteries

Li-Ion batteries are generally classified as dangerous goods

Vehicles with installed (safe or damaged) Li-Ion-batteries are excepted from dangerous goods regulation for road transport

But: For transports apply standards and regulations of road safety (including usual safety measures to avoid or reduce safety potential hazards)
Transport of Li-ion-Batteries

Series batteries (38.3 tested)

- **new\used batteries**
  - Transport according to **P903**
    - labeling and handling as dangerous good

- **damaged/ not transport safe batteries**
  - Transport according to **SP 661** (since 2013) or according to Multilateral Agreement **M259**
    - (only valid in states that have signed)

- **Weight < 35 kg:**
  - labeling and handling as dangerous good

- **Weight > 35 kg:**
  - Approval according to A99 by agency (LBA) from departure state
    - (only ex departure state valid)

- **At this time not possible!**
  - From 2015 onwards sea transport is regulated as road transport (SP 376)

Prototype batteries

- **new\used batteries**
  - Transport according to **SP 310**
    - usage of package according to packing group I
    - labeling and handling as dangerous good

- **damaged/ not transport safe batteries**
  - Transport according to **SP 661** (since 2013) or according to Multilateral Agreement **M259**
    - (only valid in states that have signed)

- At this time not possible!
  - From 2015 onwards sea transport is regulated as road transport (SP 376)

- Approval according to A88 by agency (LBA) from departure state
  - (only ex departure state valid)

- to/by/over USA additional approval by agency (DOT)

- At this time not possible!

Effective Sep. 2013
Test Series for Transportation Approval according to UA 38.3 UN Manual of Tests and Criteria

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Test cycle / period</th>
<th>Li-Cell</th>
<th>Li-Battery</th>
<th>Test criteria</th>
</tr>
</thead>
</table>
| 1. Altitude simulation              | Min. 6 hrs                                                | ✔️       | ✔️         | ➤ No loss of mass  
➤ No leakage  
➤ No exhaust  
➤ No degradation  
➤ No fracture  
➤ No fire  
➤ Off-load voltage after test ≥ 90% before test |
| (p ≤ 11.6 kPa at 20 ± 5°C)          |                                                          |         |            |                                                                                |
| 2. Thermal test                     | 10 x 6 hrs (12) + 6 hrs (12) + 24 hrs storage at 20 ± 5°C | ✔️       | ✔️         |                                                                                |
| (72 ± 2°C / -40 ± 2°C)              |                                                          |         |            |                                                                                |
| 3. Vibration (1 – 8gn)              | 12 x 15 min. in 3 hrs on 3 axis                           | ✔️       | ✔️         |                                                                                |
| 4. Shock (150gn/50gn)               | 3 strikes in each direction (=18x)                        | ✔️       | ✔️         |                                                                                |
| 5. External short circuit           | Less than 0.1 Ohm for 1 hrs at 55 ± 2°C, 6 hrs monitoring| ✔️       | ✔️         |                                                                                |
| 6. Impact/Crush                     | 1 x each axis, 6 hrs monitoring                          | ✔️       | Not required | No degradation  
No fire within 7 days after the test |
| (9.1 ± 0.1 kg from 0.61 ± 2.5 cm height) | (crushing speed = 1.5cm/s)                              |         |            |                                                                                |
| 7. Overcharge                       | Test duration 24 hrs 7 days monitoring                    | Not required | ✔️        |                                                                                |
| 8. Forced discharge                 | 1 discharge / cell 7 days monitoring                      | ✔️       | Not required |                                                                                |

References

➤ Tests T.1 to T.5 must be executed at the same cell / battery.  
➤ Test T.7 may be executed at batteries used in the tests T.1 to T.5.  
➤ Number of tested samples = 2 - 8 Batteries according to 38.3.3 (b) and (d)  
➤ Facilites applicable for „battery assemblies“.  

gn = „Ground acceleration“
Validation of transport ability from LIB

A: Critical Safety Inspection
   A1: Smoke
   A2: Fire
   A3: Heating
   A4: Electrolyte leakage

B: Inspection for Physical Damage
   B1: Cracks or holes
   B2: Deformation

C: Electrical Isolation Inspection
   C1: Voltage > 20 V between HV-poles and enclosure

D: Communications Check
   D1: Isolation errors/Voltage drop of single cells
Approval needed for Transport of damaged LIB’s

Agency authorization (BAM) **for a packaging method** to transport damaged batteries by road (ADR) necessary:

- Can be used for carriage within all ADR Member States
- Cell and Battery type
- Preparation prior carriage
- Packing method
- Specification for packaging's
- Specifications for vehicles, drivers, marking and placarding
- Transport document
- Special training for personnel
- Further specifications (e.g. loading unloading in a public place forbidden...)
Packing of Li-ion Batteries

Transport box

Inner packages

Transport document

Departure Check list

Packing instruction
Summary

- Li-ion batteries in consumer products noticeable in the past with fire problems.
- Existing safety standards for Li-ion batteries predominantly applicable for cell and module behavior.
- Realistic safety standards for automotive scope have to consider complete battery system behavior.
- For vehicle accidents a safe integration of HV-batteries has a mayor importance.
- Simulation of battery behavior during crash situations is currently an important challenge.
- Experience in transporting damaged Li-ion-batteries using the new regulations (fully deployment for road/sea in 2015) has to be gained.
Thank you for your attention