



**Ostfalia**

Hochschule für angewandte  
Wissenschaften

# Safety of lithium ion batteries for automotive applications

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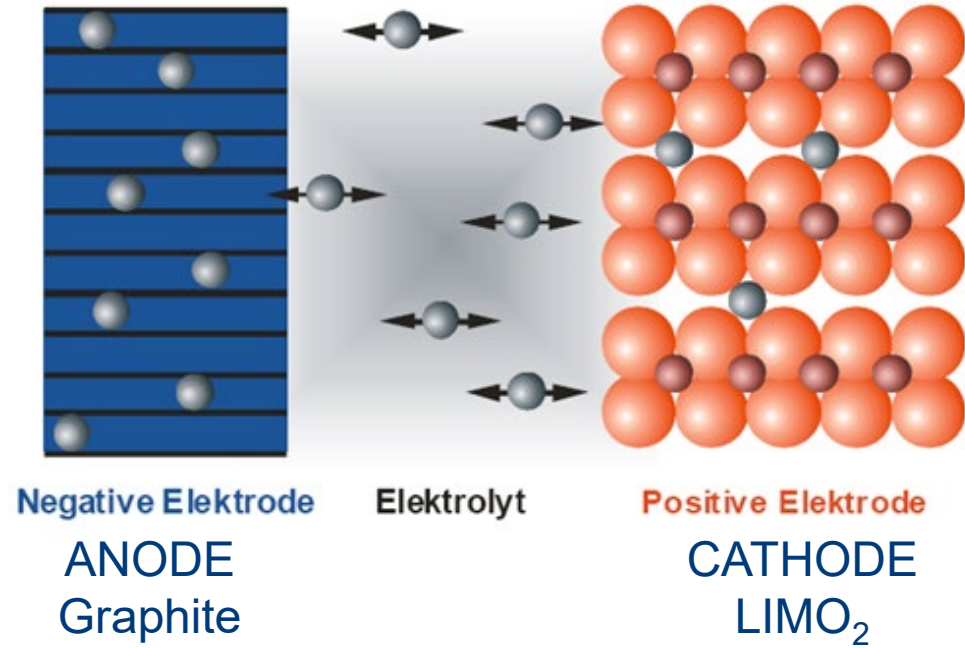


## AGENDA

- 1. How does a Lithium Ion Battery work?**
- 2. Materials and Variants of Lithium Ion Batteries**
- 3. Cathode / Safety**
  - Thermal runaway**
  - Nail penetration test**
  - Overcharging**
- 4. Safety risks- Possible failure mechanisms**
- 5. Active / passive safety**
- 6. Lithium Ion Battery Systems for vehicles**

# 1. How does a Lithium Ion Battery work?

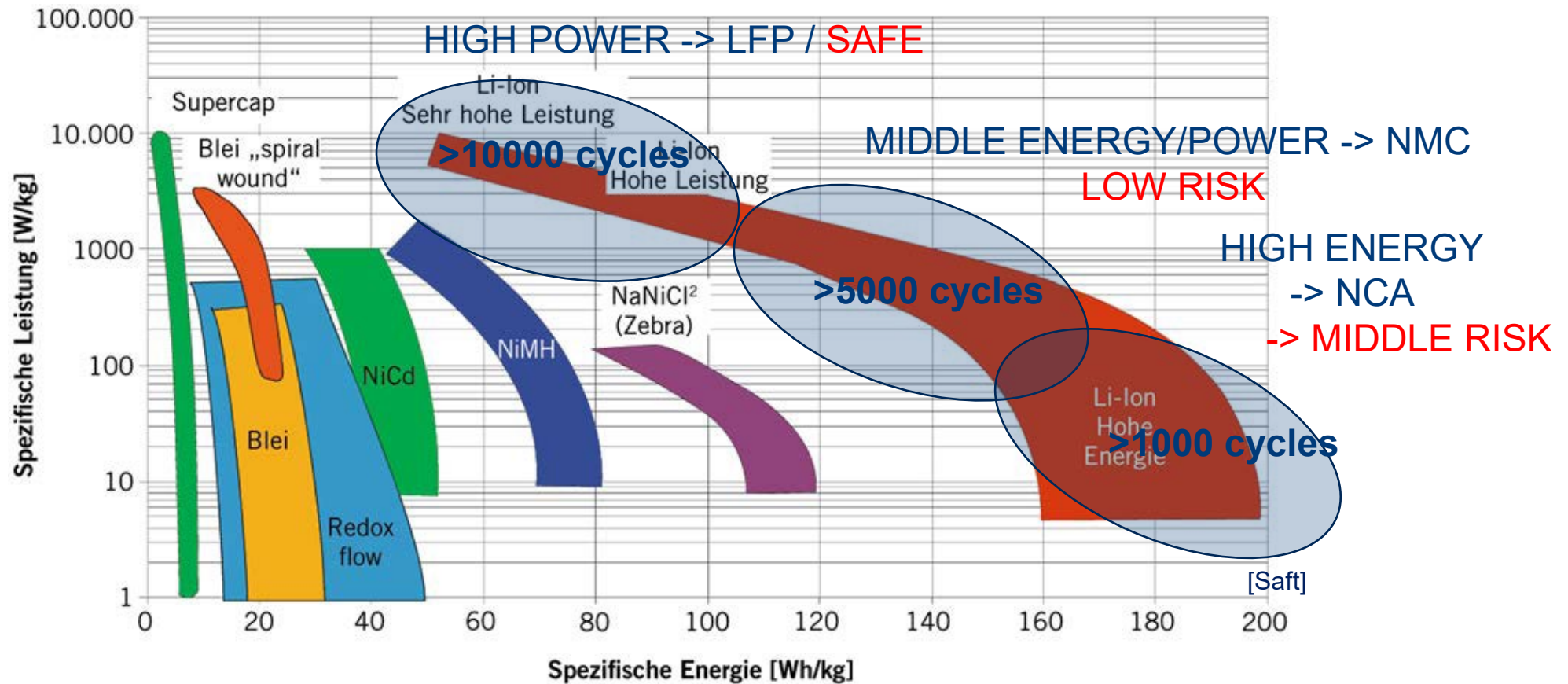
## Rocking chair model



Quelle: IMFAA, HS Aalen

## 2. Materials and Variants of Lithium Ion Batteries

Lithium Ion batteries deliver a realistic chance for pure electric driving



## 2. Materials and variants of Lithium Ion Batteries

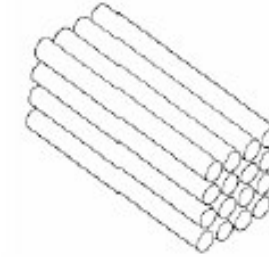
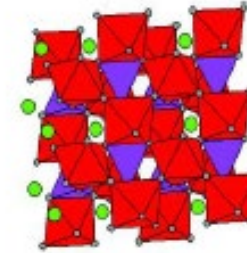
### CATHODE

- LFP  
(Lithium-Iron-Phosphate)

**SAFE**

Olivin Structure

(1D-movement)

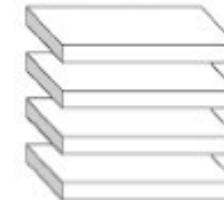
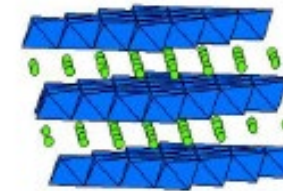


- NMC (LCO)  
Lithium-Nickel-Manganese-Cobalt-Oxide

**LOW RISK**

Layer structure

(2D-movement)

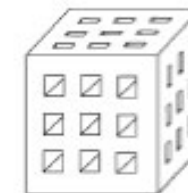


- NCA  
Lithium-Nickel-Cobalt-Aluminum-Oxide

**MIDDLE RISK**

Spinell structure

(3D-Movement)



[1-Tuebke]



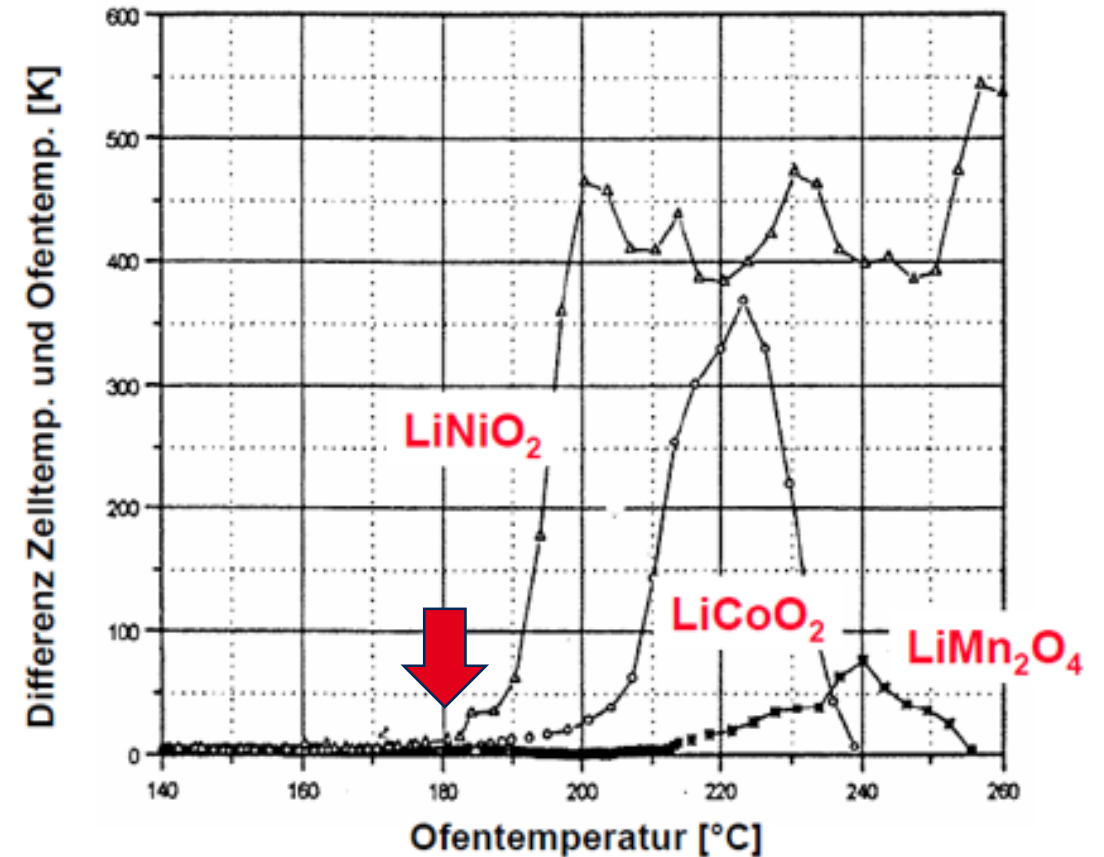
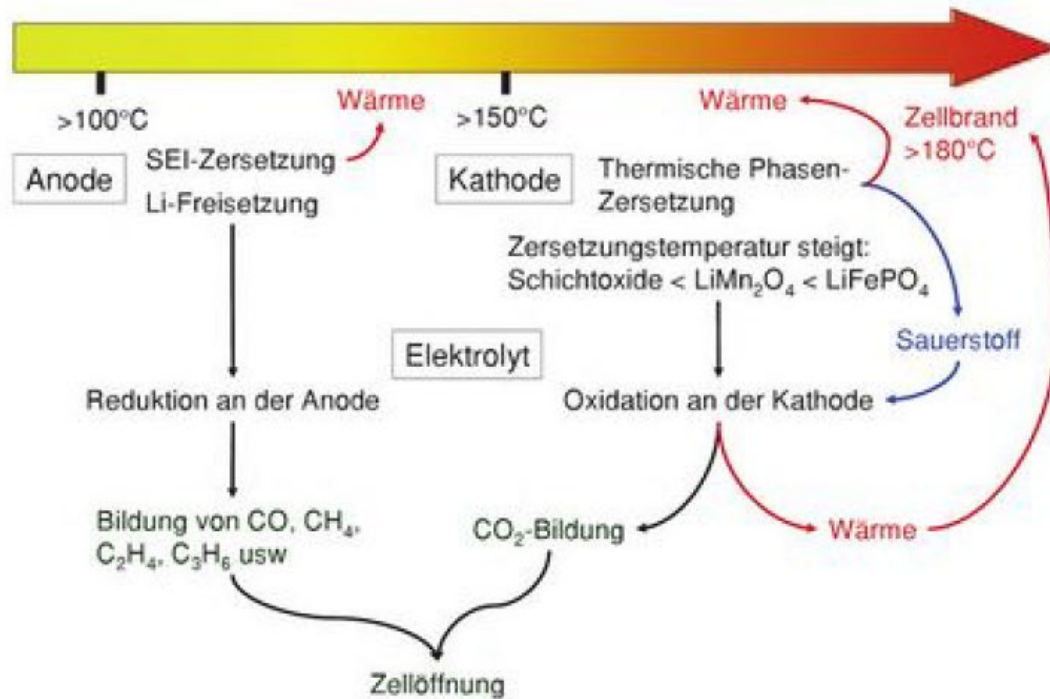
### 3. Cathode / Safety

Overview Abuse Tests		
Mechanisch	Thermisch	Elektrisch
Controlled Crush	Thermal Stability	Short Circuit
Drop	Simulated Fuel Fire	Partial Short Circuit
Penetration	Elevated Temperature Storage	Overcharge / Overvoltage
Roll-over Simulation	Rapid Charge / Discharge	Overdischarge / Voltage Reversal
Immersion	Thermal Shock Cycling	
Mechanical Shock		

### 3. Cathode / Safety

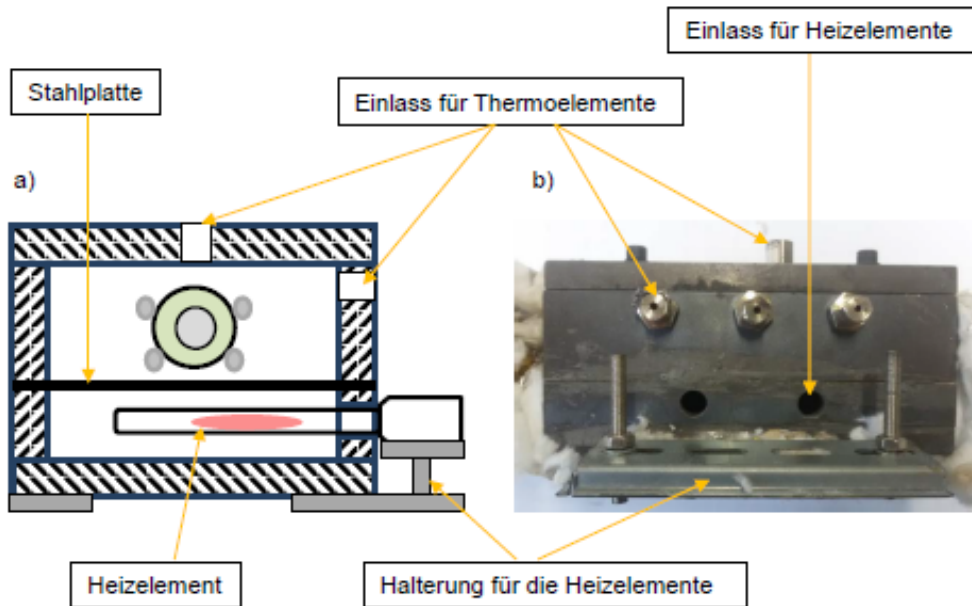
#### Thermal Runaway at Lithium Ion Cells:

(AA – Zellen im Ofen aufgeheizt mit 2,2 K/min)



### 3. Cathode / Safety

#### Thermal Runaway of Lithium Ion Cells:



NCA – NCR18650B  
Panasonic 3400 mAh  
 $Ni_{0,85}Co_{0,1}Al_{0,05}$



NMC – ICR18650-22P  
Samsung 2150 mAh  
 $N_{1/3}M_{1/3}C_{1/3}$

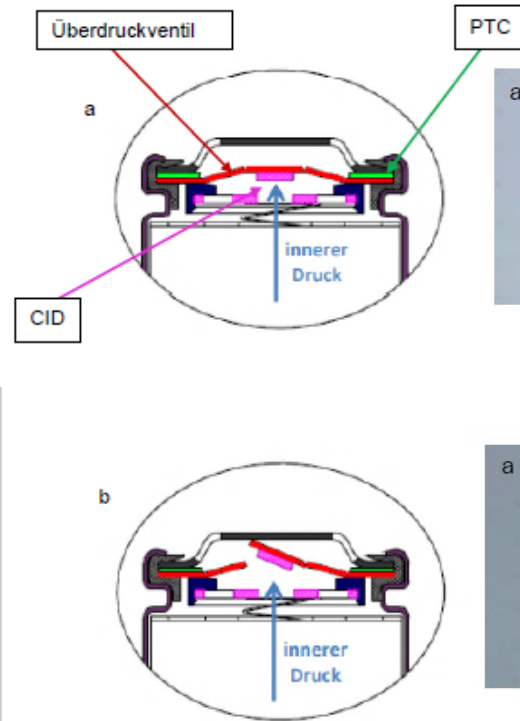
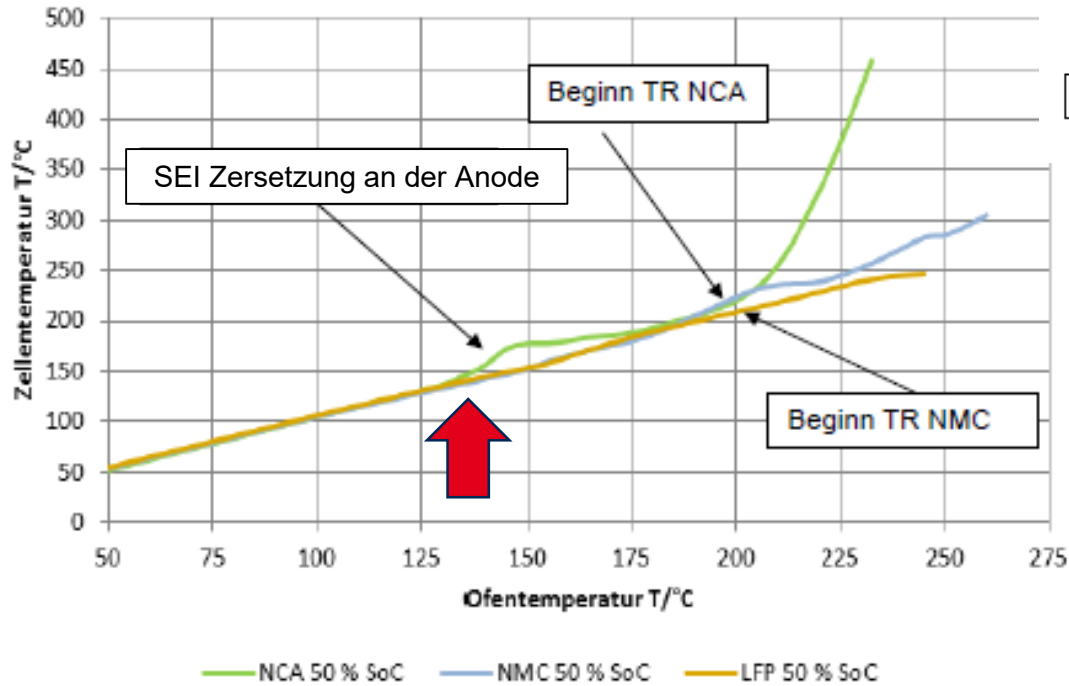


A123 – APR18650M-1A  
Samsung 1100 mAh  
LFP

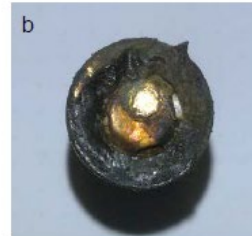


### 3. Cathode / Safety

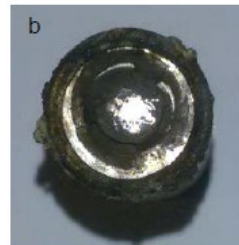
#### Thermal Runaway of Lithium Ion Cells:



LFP 50%



NMC 50%

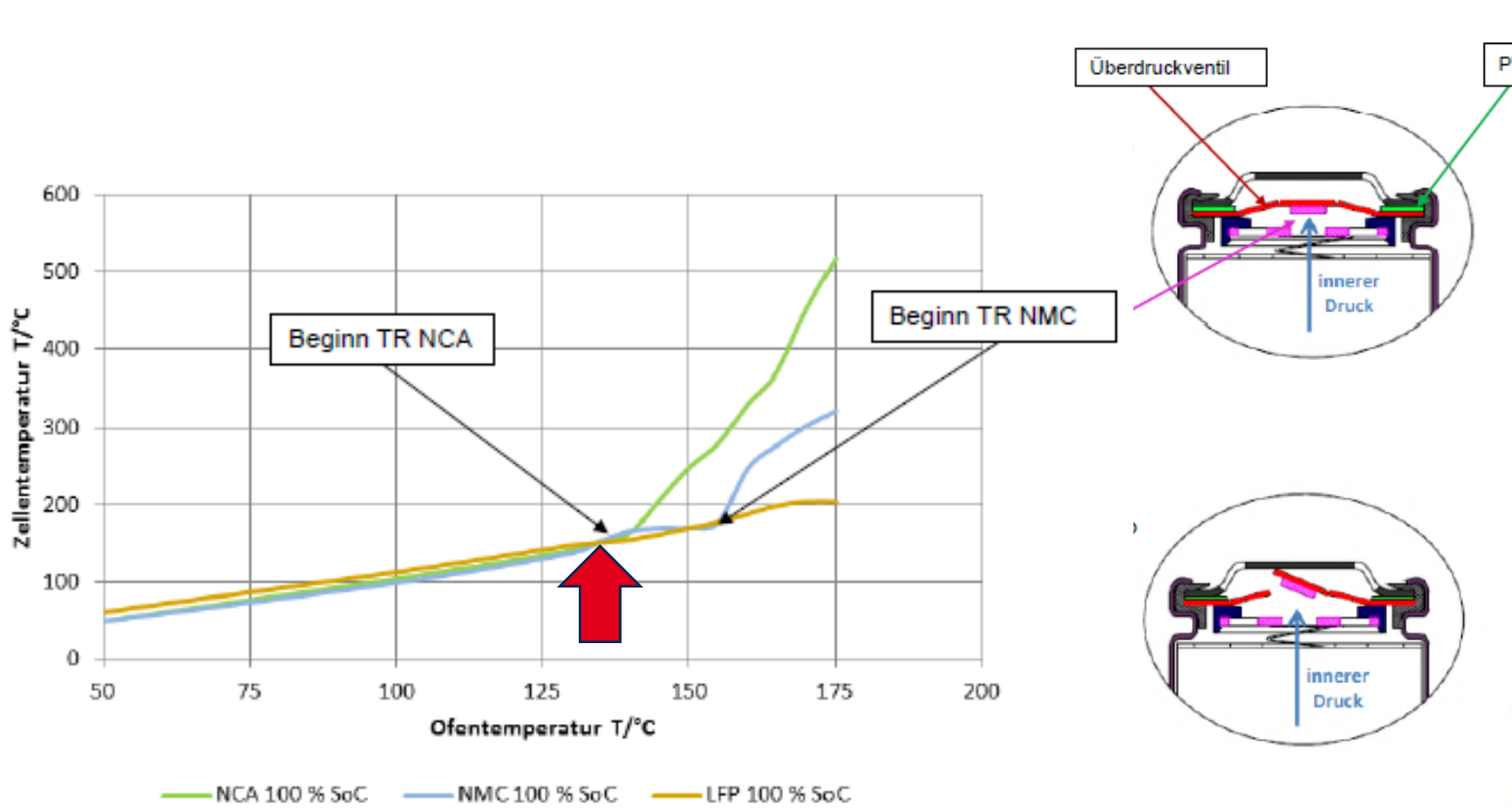


NCA 50%

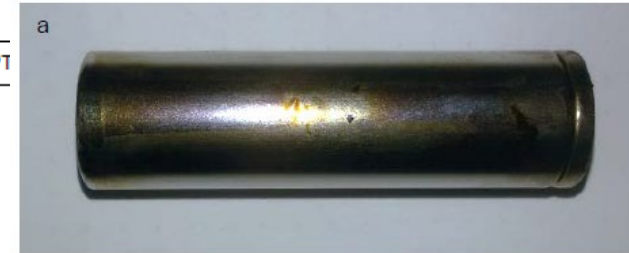


### 3. Cathode / Safety

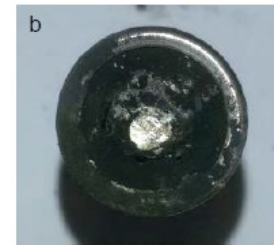
#### Thermal Runaway of Lithium Ion Cells:



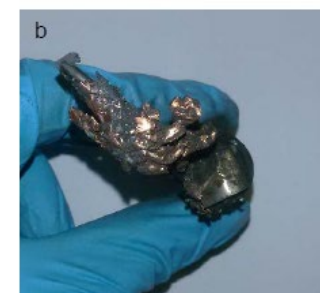
LFP-100%



NMC 100%

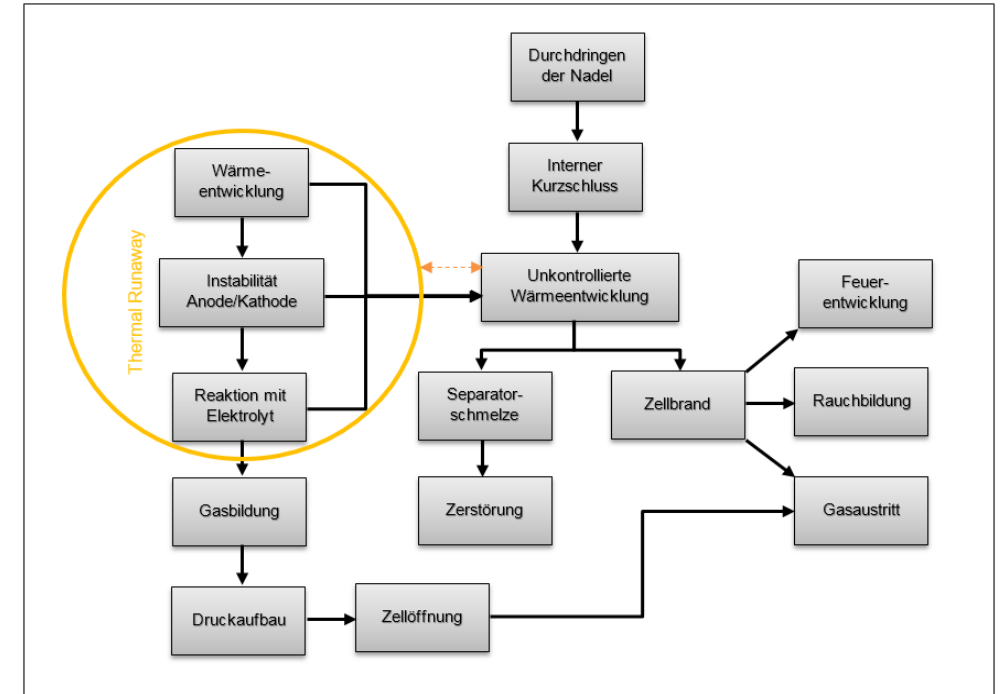
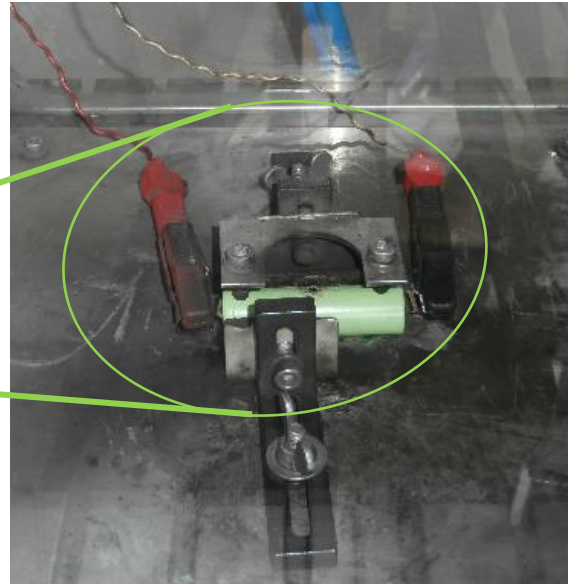
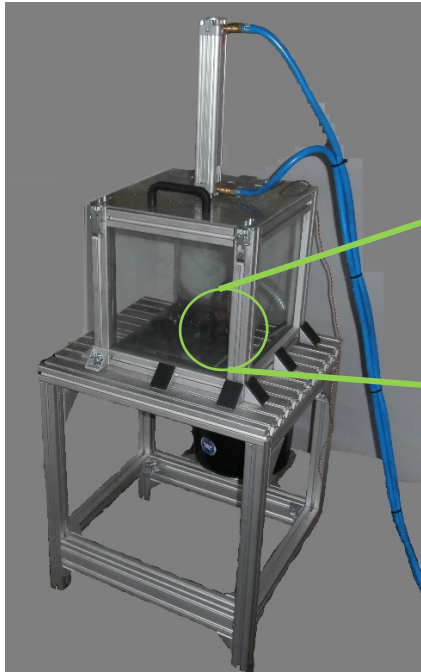


NCA 100%



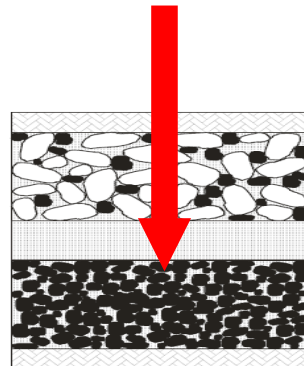
### 3. Cathode / Safety

#### Nail Penetration Test



#### Nail Penetration Test:

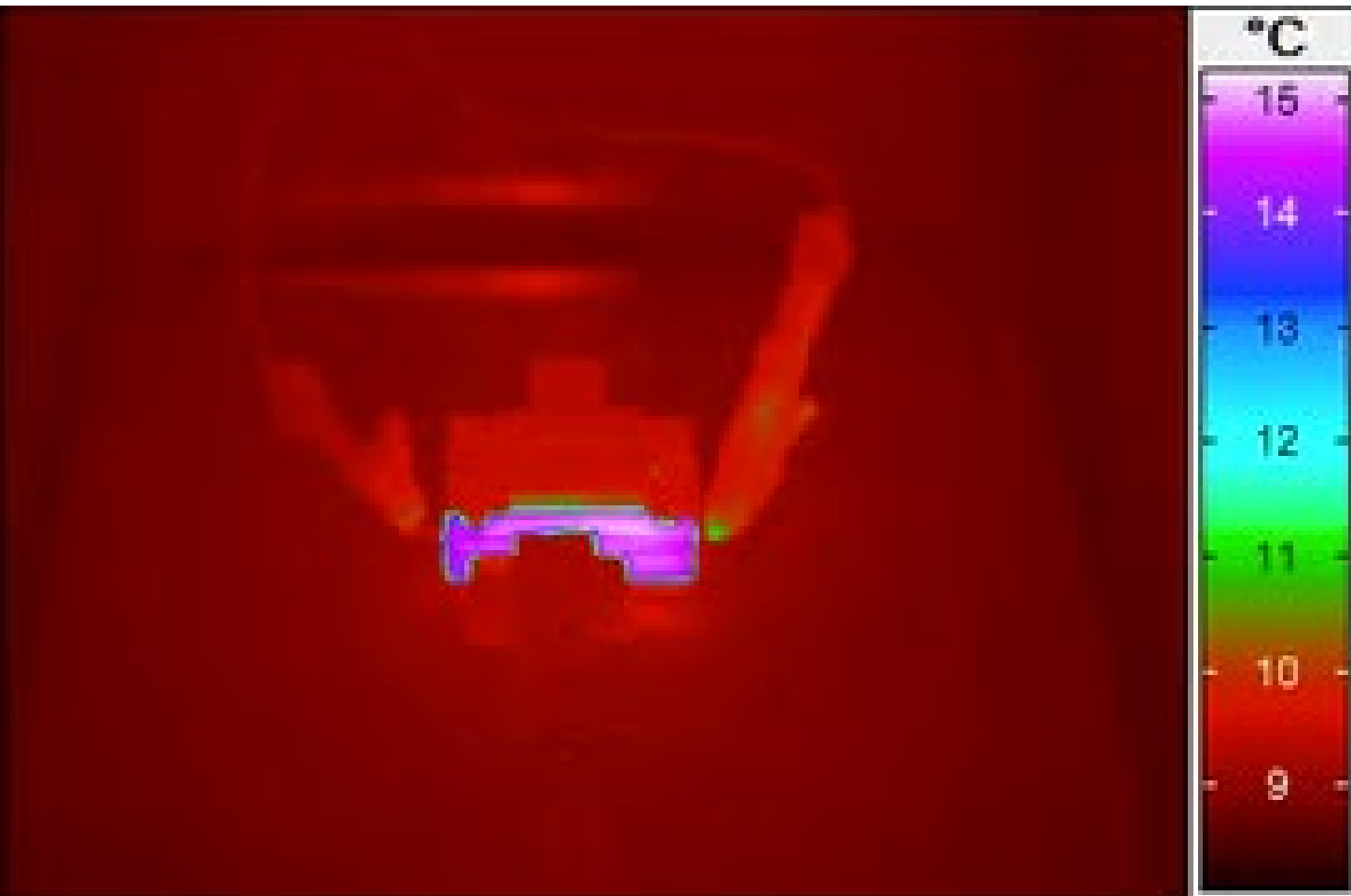
- Needle diameter: 3 mm
- Direction: vertical to the electrode
- Penetration depth: through the cell
- Position: middle



### 3. Cathode / Safety

## Nail Penetration Test

### IR-Thermography of the LFP-cell



- LFP cell are very safe
- No degasing because of the stable cathode phosphate structure
- Small increase in temperature

### 3. Cathode / Safety

#### Nail Penetration Test

Video of the NMC Cell



The reaction products (! ~3 Liter /Ah !)

CO<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub>F (Fluormethan), HF, O<sub>2</sub>, N<sub>2</sub>,  
H<sub>2</sub>, CO, CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>8</sub>, Phosphin,  
Formaldehyd, Acetaldehyd, Naphtalin,  
Fluoren, Pyren, Chrysen, Propionaldehyd,  
Butryaldehyd, Phenol, 1,2 Ethandiol, Pyridin,  
Carbonsäurediethylester,...

Metall dust particles

Al, Ca, Co, Cu, Fe, Li, Mn, Na, Ni, Ph, Zn,...

Toxic / Flammable -> Explosive / Pollutant /  
carcinogenic

### 3. Cathode / Safety

#### Nail Penetration Test

Video of the NCA cell

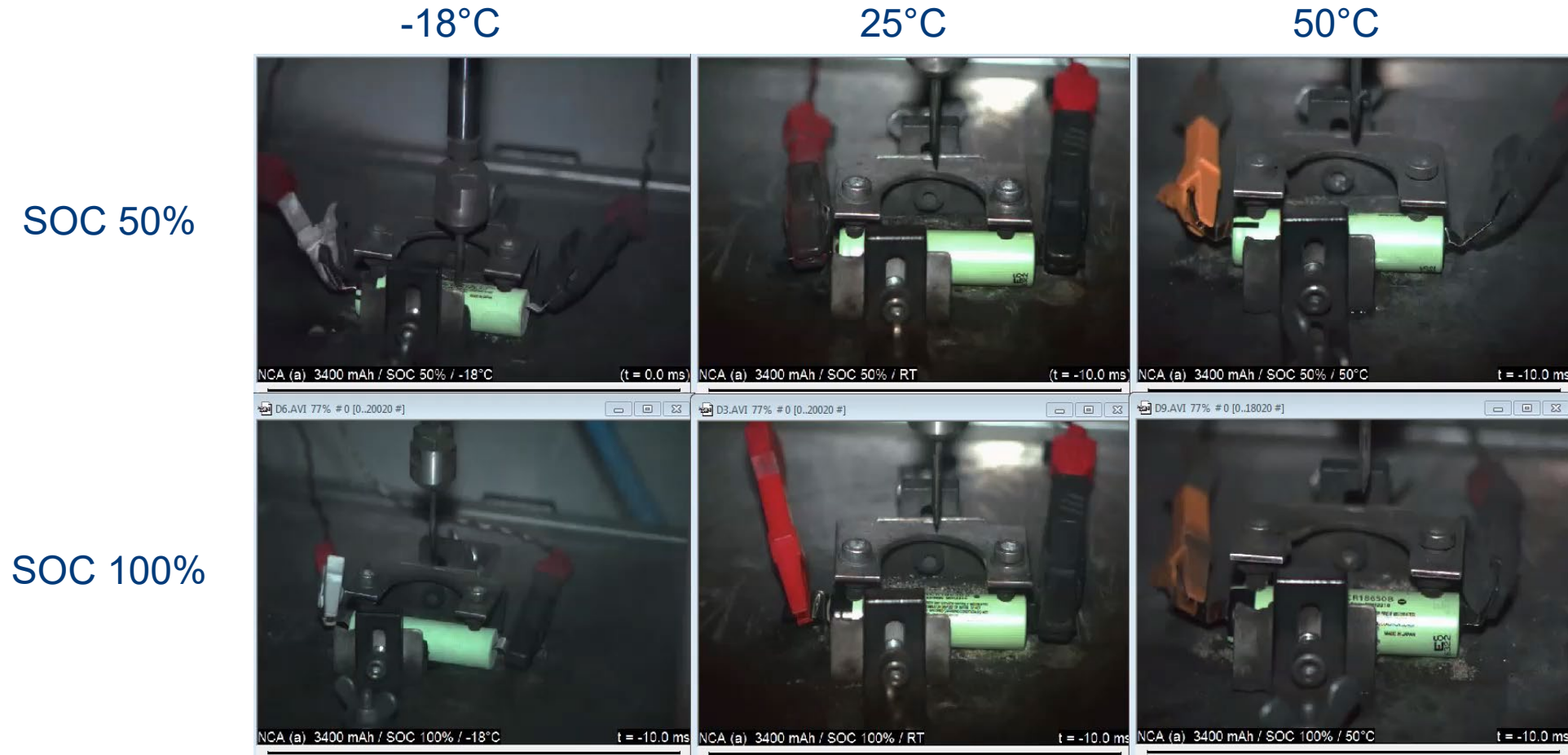
High Speed Video recording of the NCA cell



### 3. Cathode / Safety

#### Nail Penetration Test

High Speed Video - NCA Panasonic-Cell with 50% / 100% SOC at different temperatures (-18°C/25°C/50°C)



### 3. Cathodes / Safety

#### Nail Penetration Test

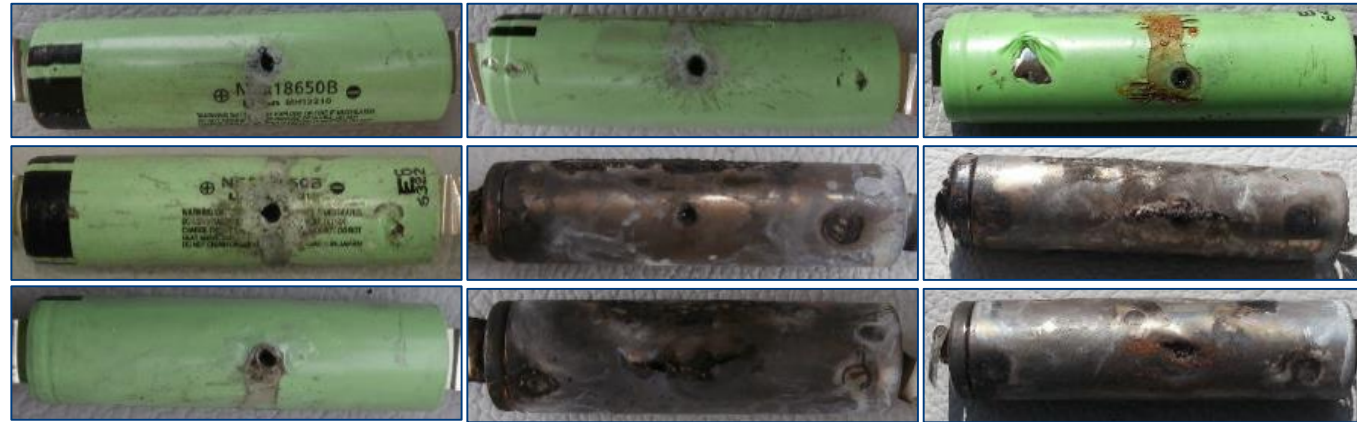
Comparison Panasonic/LG NCA-cell

Temperature →



NCA-Zelle  
(Panasonic)

S  
O  
C ↓



- High energy density (>240 Wh/kg)
- Increasing reactivity with higher SOC and temperature

Temperature →



NCA-Zelle  
(LG)

S  
O  
C ↓

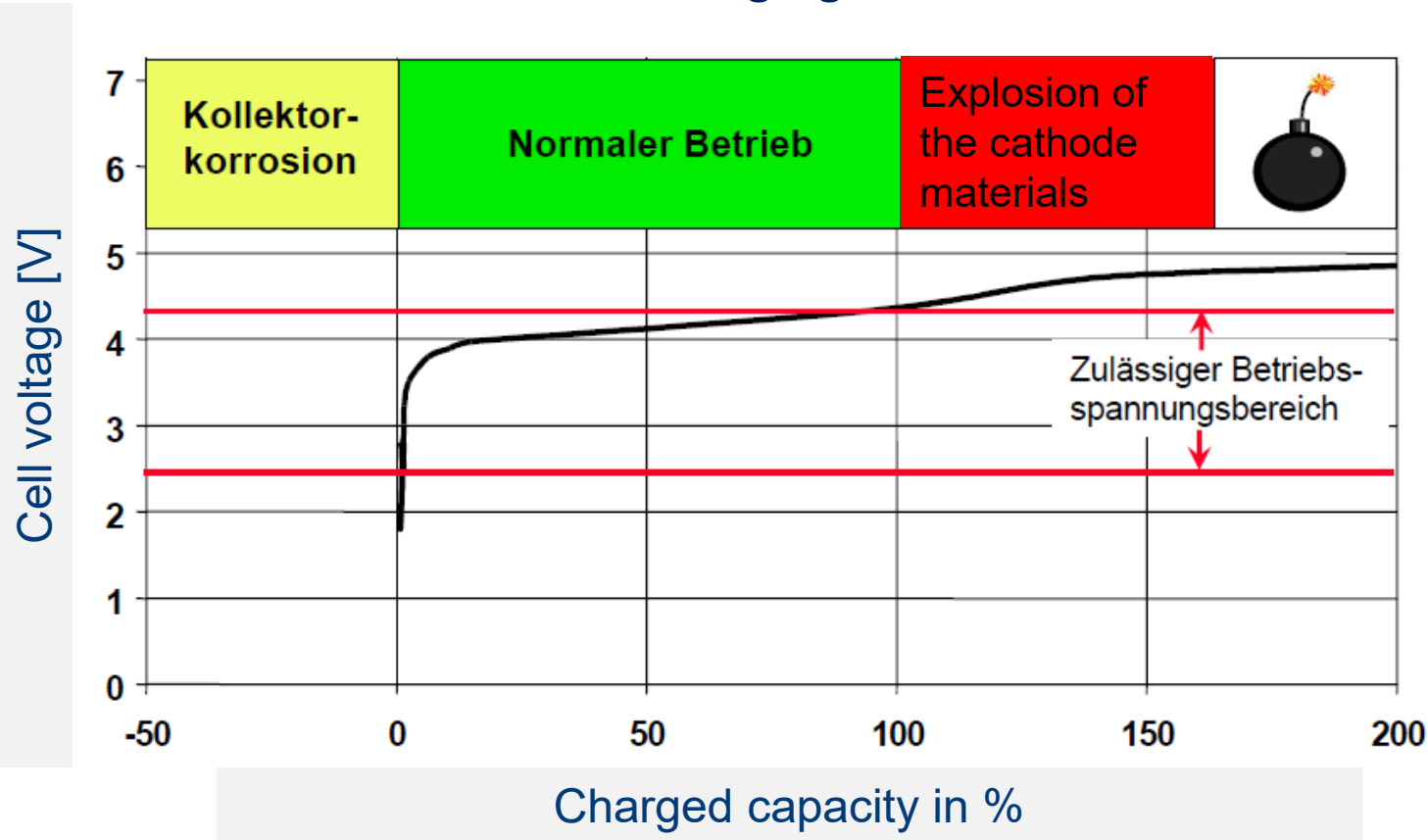


- Worse damage picture
- Burst of the cell housing
- lower inner resistance 0,06 Ohm compared to the Panasonic cell mit 0,11 Ohm.

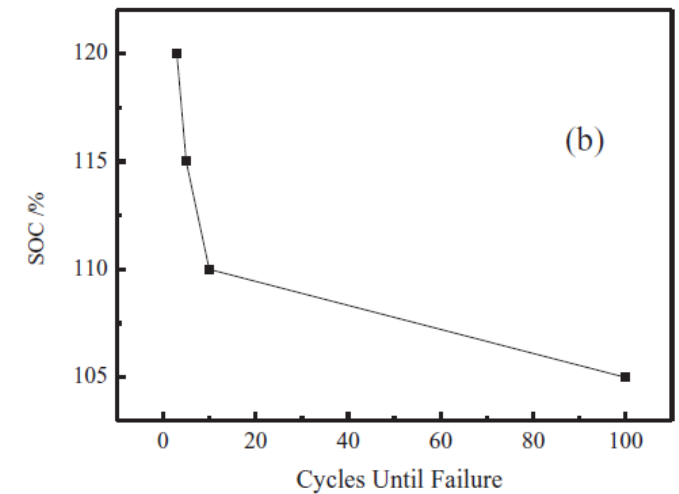
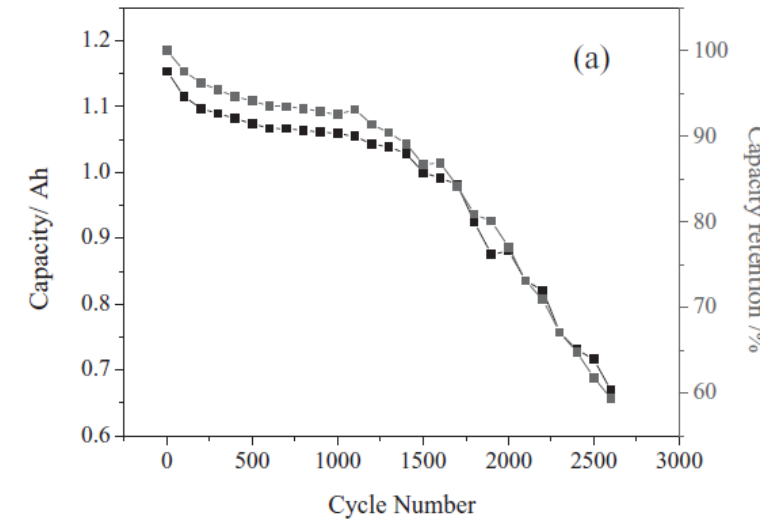


### 3. Cathode / Safety

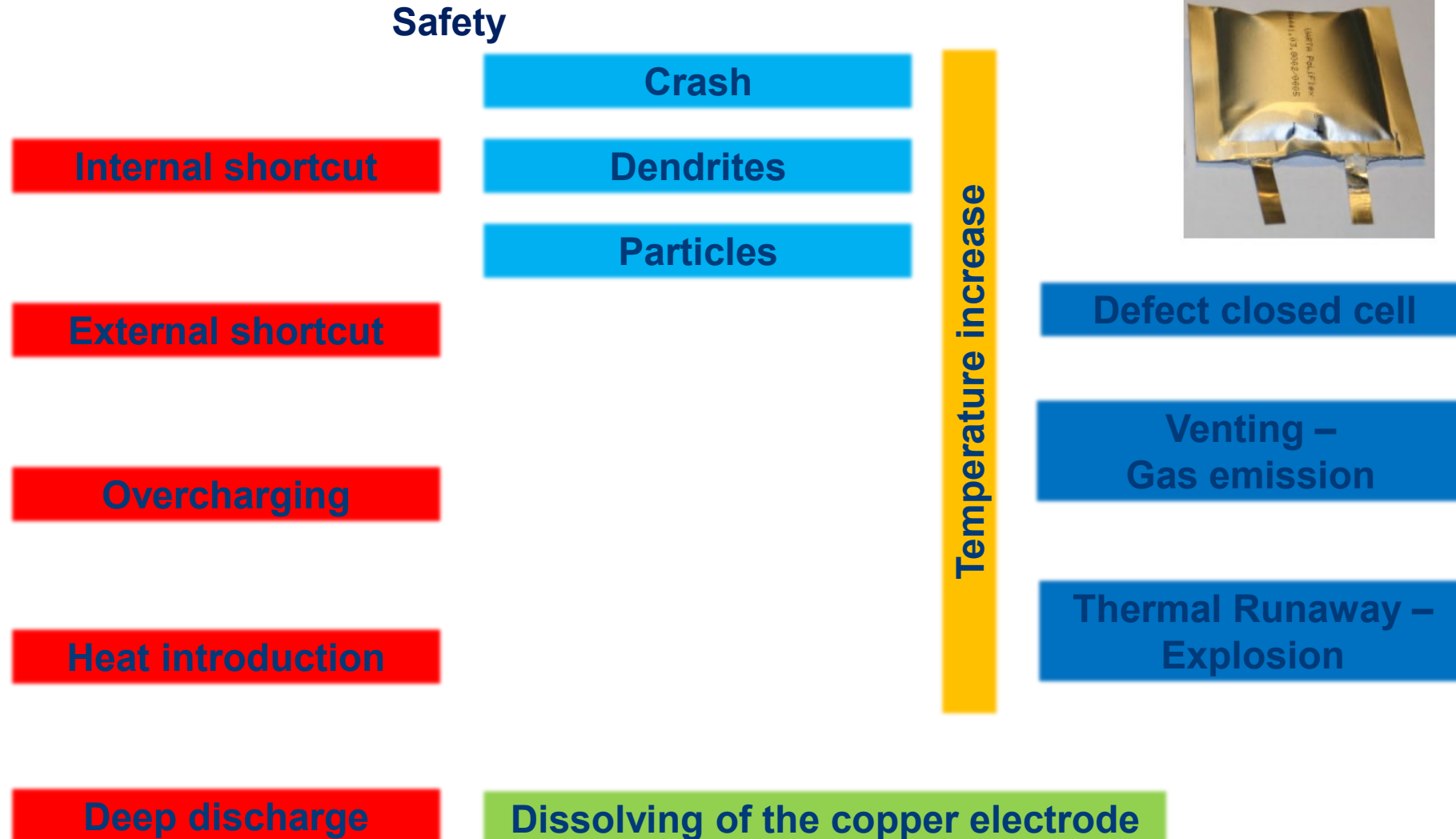
#### Overcharging



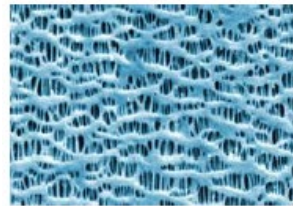
[3-Sauer]



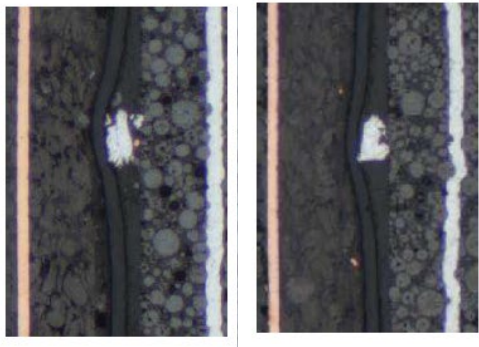
## 4. Safety risks- Possible failure mechanisms



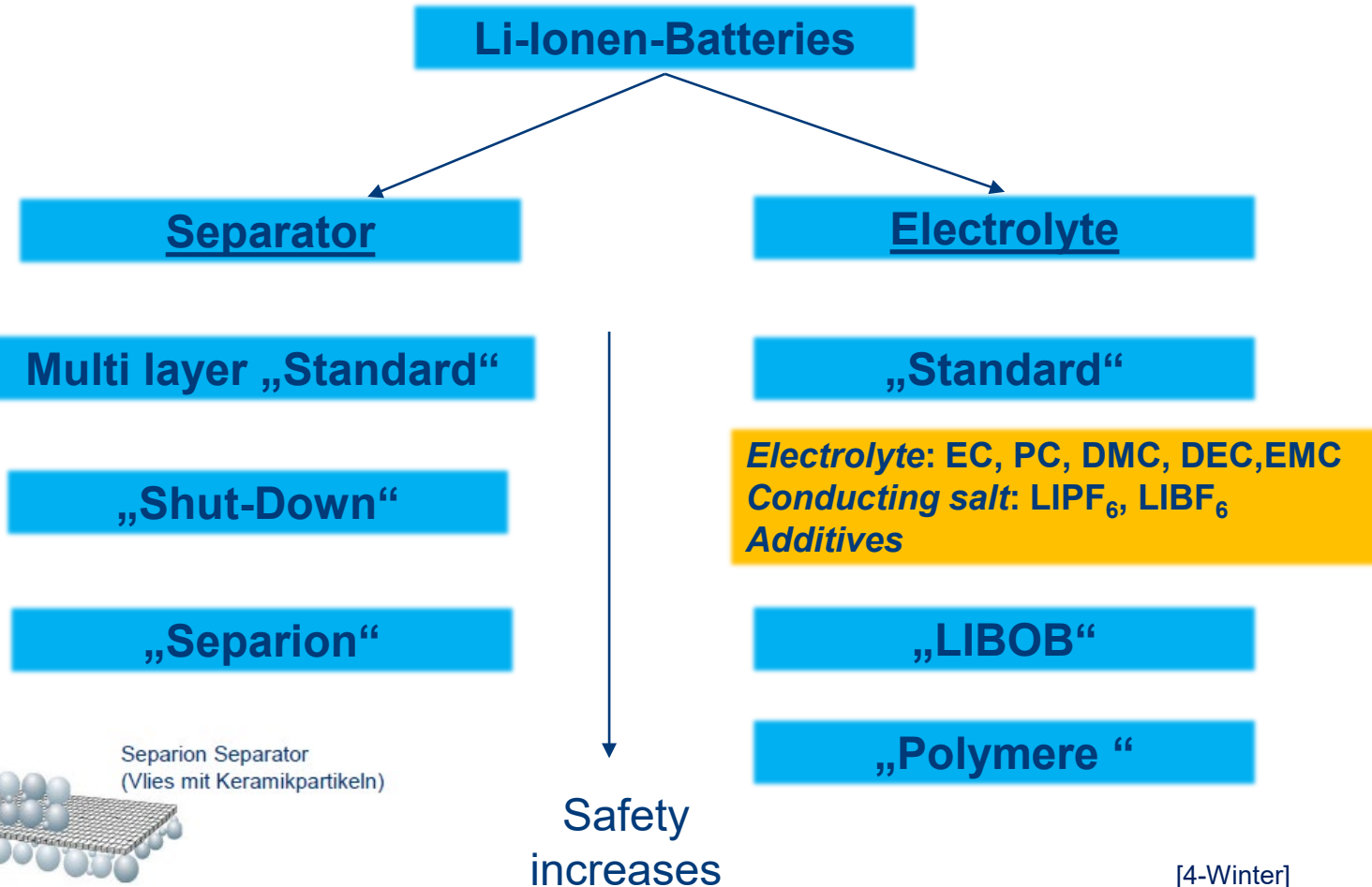
## 5. How to make batteries safer on the cell level -> passive safety



Celgard Separator  
(3-lagiger Polyolefin-Sep.)



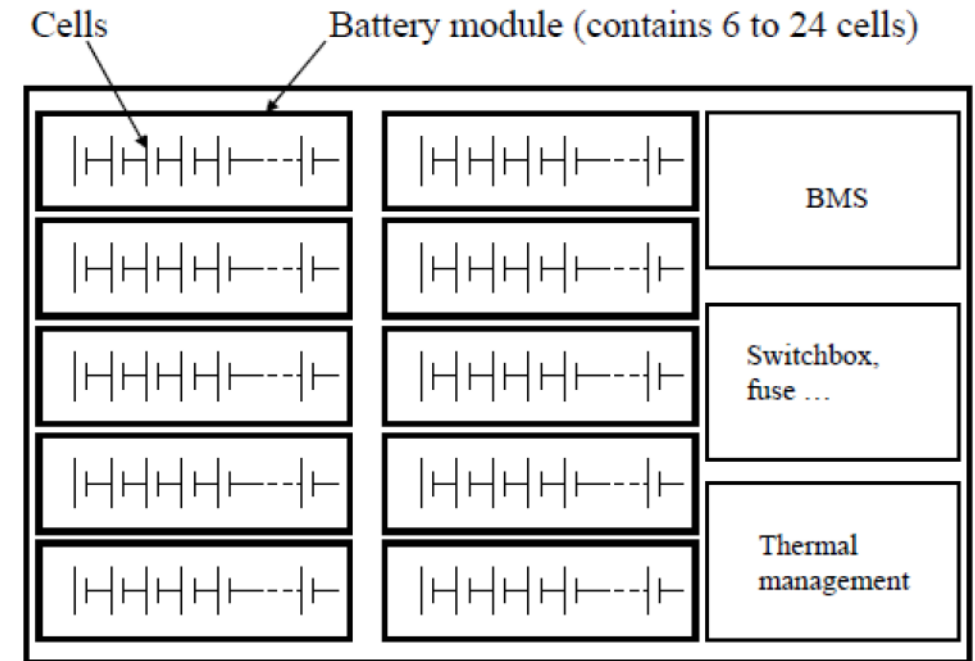
Separion Separator  
(Vlies mit Keramikpartikeln)



[4-Winter]

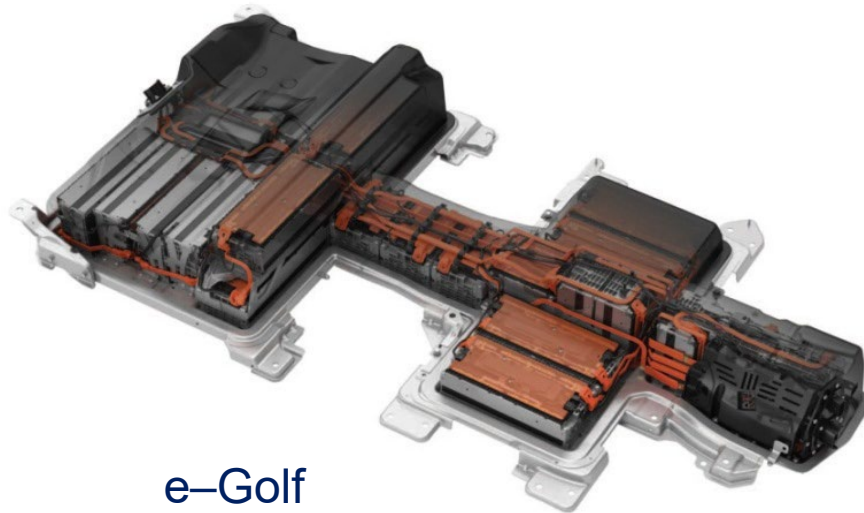
## 6. Lithium Ionen Battery Systems for vehicles -> active safety

- Big battery packs exist out of modules
- The module controls the temperature, current and voltage of each cell
- Master / slave layout of the BMS
- A thermal management system with active cooling/heating is recommended
- The moduls are mounted in a crash safe, water proof containment

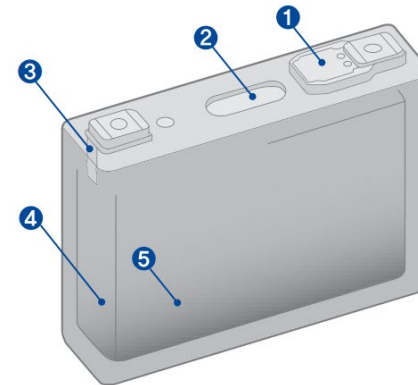


## 6. Lithium Ionen Battery Systems for vehicles

### Layout 1: NMC-Prismatic cell



Samsung

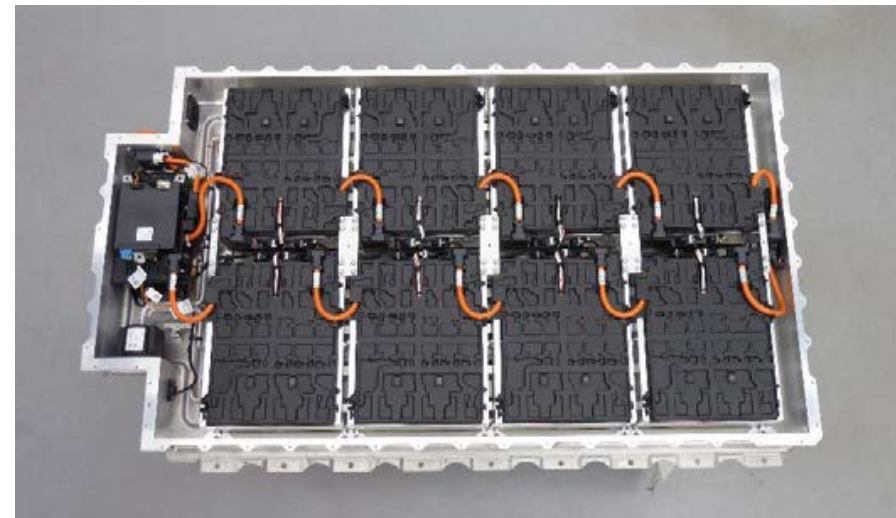


Multi-layered protection on cell

- 1 OSD (Overcharge Safety Device)
- 2 Vent
- 3 Fuse
- 4 SFL (Safety Functional Layer)
- 5 NSD (Nail Safety Device)\*

\* In case of 94Ah cell

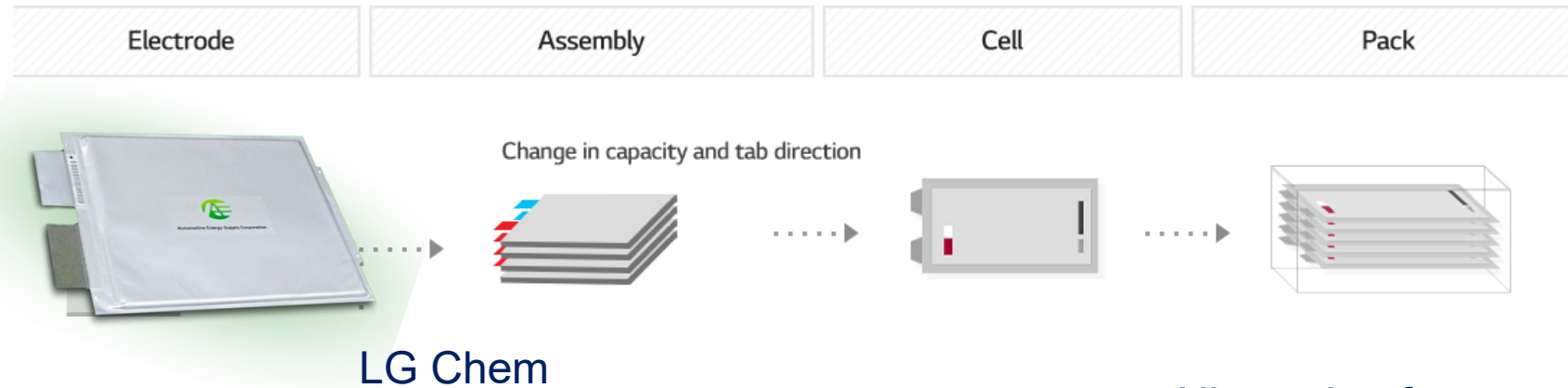
Large cells (>60 Ah/kg) with higher energy densities (>180 Wh/kg) can become critical Cost intensive cells



BMW i3

## 6. Lithium Ionen Battery Systems for vehicles

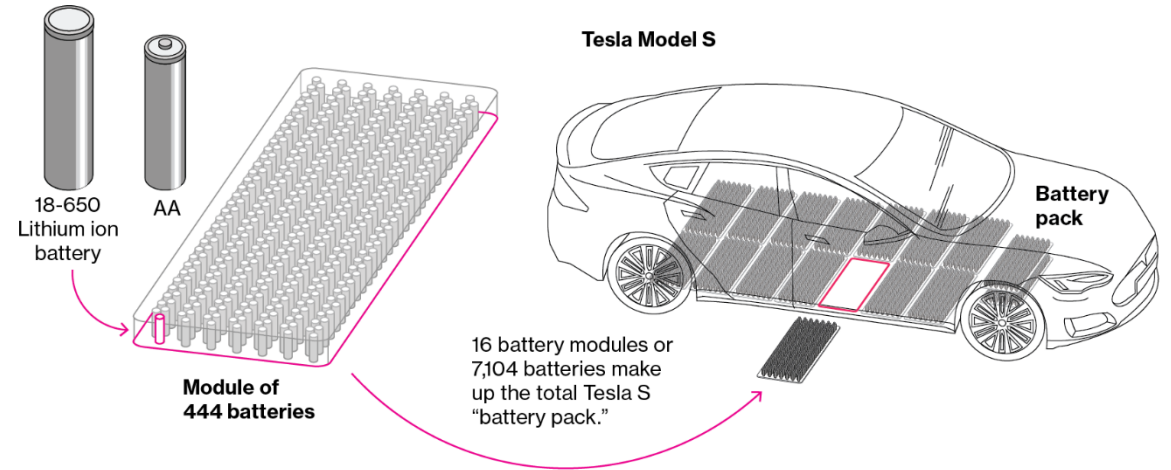
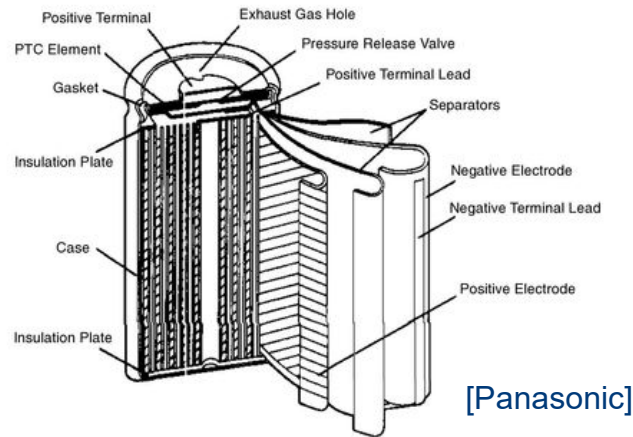
### Layout 2: NMC-Pouch bag cell



The Battery container has to fullfill all of the safety demands.  
Most critical for higher energy densities!  
Economical sollution

## 6. Lithium Ionen Battery Systems for vehicles

### Layout 3: NCA - Round cells



[teslarati]

Cells with the highest energy density, highest safety risk -> only small cells 18650/21700/ ?4680?  
Massive battery container with single cell protection, active cooling/heating  
Most economical solution



## Summary

### To increase the safety of Lithium Ion Batteries for automotive applications

#### Passive safety at cell level

- Choice of anode and cathode materials
- shut down/ multi layer /ceramic separator
- Safety features in the electrolyte
- Vent membran, PTC element, mechanical protection against penetration

#### Active safety on module and system level

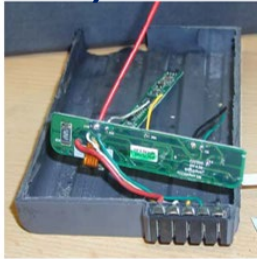
- Intelligent voltage management, protection against over-/undercharging
- Temperature-management with heating/cooling
- Second level mechanical protection





## Summary

**Failure (Dell-2006)  
Laptop–Akku**



**Failure Samsung  
Galaxy Note 7  
2016**



**Failure Boeing  
Dreamliner  
2014**



**Failure Tesla  
Model S  
2018**



**Failure Tesla  
Model S  
20120**



**Increasing the passive and active safety are necessary  
but are no garantie for safe operation!  
a final risk in ppm area still exists!**