5th International Conference

Automotive Battery Management Systems

18 - 20 September, 2018 | NH Collection, Frankfurt am Main, Germany

Improving BMS and TMS by combined Battery Calorimetry and modelling

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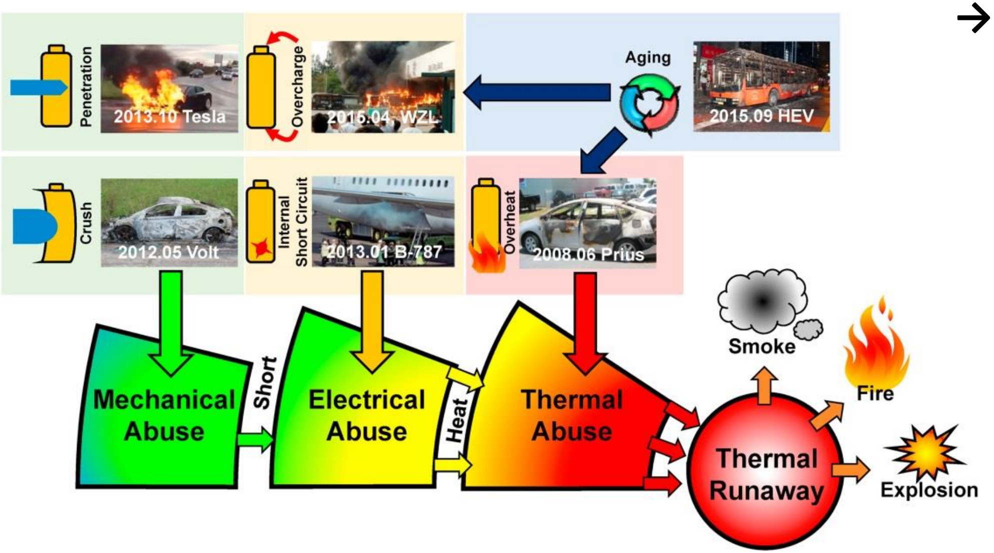
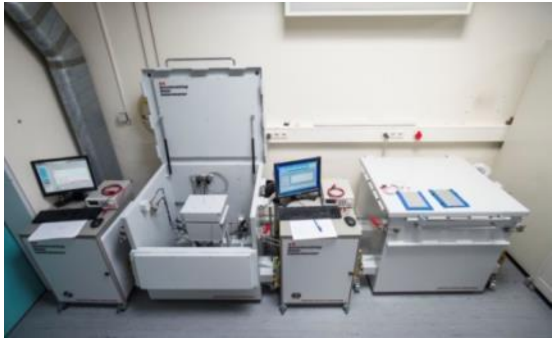
Motivation

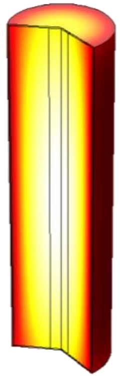
Increase of safety and reliability of lithium-ion batteries for EV/HEV



Feng et al., Energy Storage Materials 10 (2018) 246

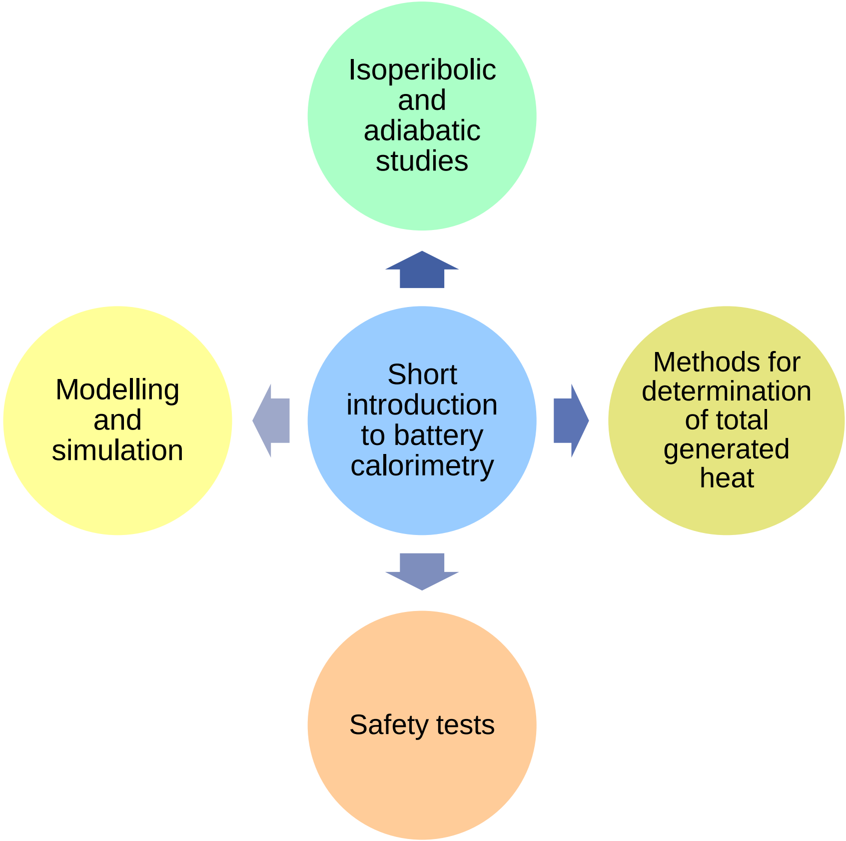
→ **For improving battery management system (BMS) and thermal management system (TMS) electrochemical and thermal behavior of the cells have to be thoroughly studied**





Aim: Improvement of TMS and BMS by determination of quantitative data using battery calorimetry in combination with modelling and simulation

Outline


Isoperibolic and adiabatic studies
Modelling and simulation
Short introduction to battery calorimetry
Methods for determination of total generated heat
Safety tests

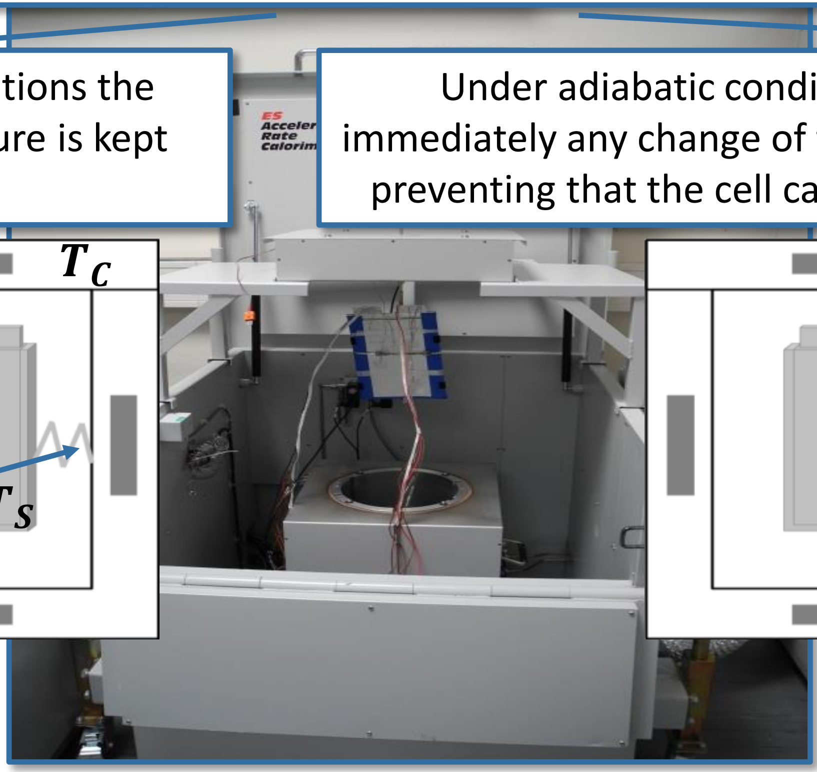
Short introduction to battery calorimetry

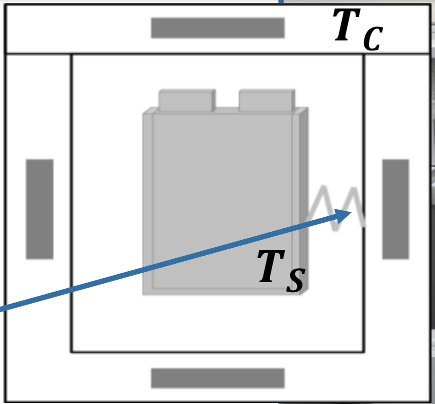
Possible conditions in an Accelerating Rate Calorimeter (ARC)

An ARC provides **isoperibolic** and **adiabatic** conditions

Under isoperibolic conditions the environmental temperature is kept constant.

Under adiabatic conditions the heaters follow immediately any change of the bomb thermocouple thus preventing that the cell can transfer heat to the walls.

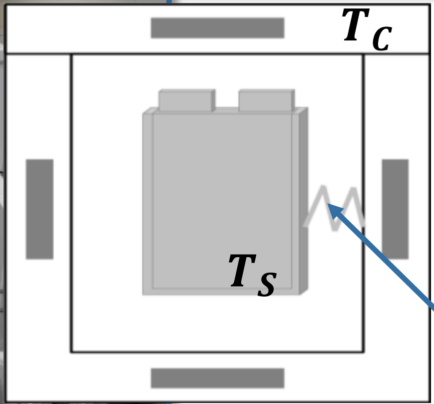




R_{th} defined

T_C constant

$T_S(t) = T_{S_0} + \alpha \cdot t$

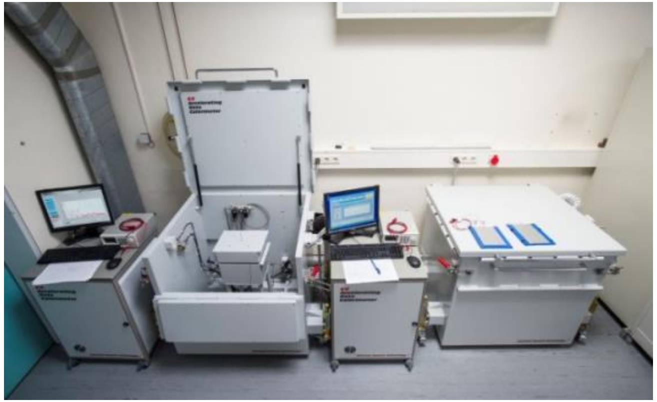


R_{th} very high

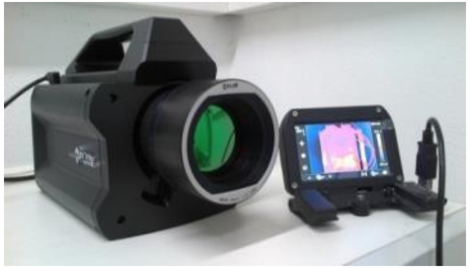
$$T_C = T_C(t) = T_{C_0} + \alpha \cdot t$$

At IAM-AWP: Europe`s Largest Calorimeter Center

Accelerating Rate Calorimeter(ARC)



Equipment: 6 ARC's (THT); 2 Tian-Calvet calorimeters (C80, Alexys1000: Setaram); DSC (Netzsch), TGA+STA (TAG, Setsys, Setaram); IR camera (FLIR); 12 Temperature chambers; 10 Cyclers; EIS (Ref3000, Gamry)



Adiabatic and Isoperibolic Measurements

Adiabatic Measurements

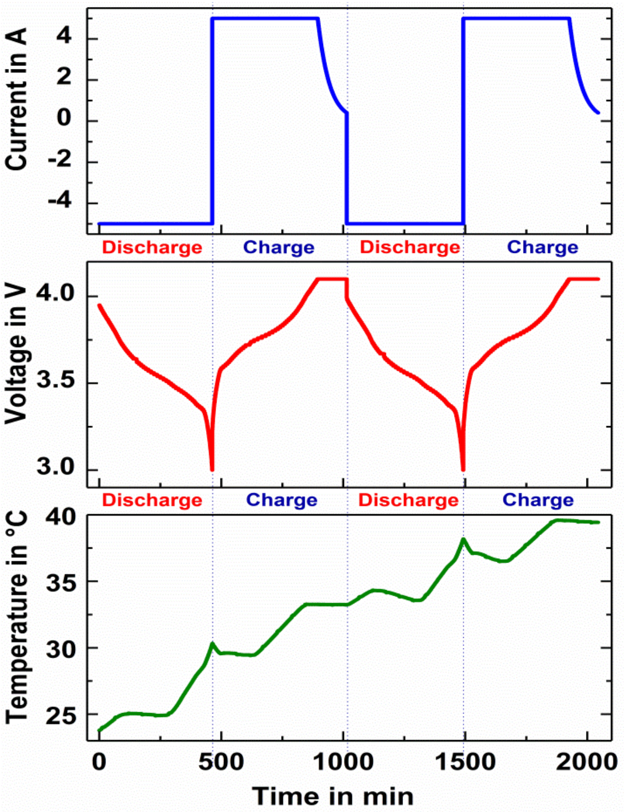
Worst Case Conditions

→ Cell in a pack surrounded by other cells

Discharge parameter:
- method: constant current (CC)
- U_{min} = 3.0V
- I = 5A → C/8-rate

Charge parameter:
- method: constant current, constant voltage (CCCV)
- U_{max} = 4.1V
- I = 5A → C/8-rate
- I_{min} = 0.5A

→ after each electrochemical cycle the cell temperature increases further



T_{st} = 23°C (RT)

Isoperibolic Measurements

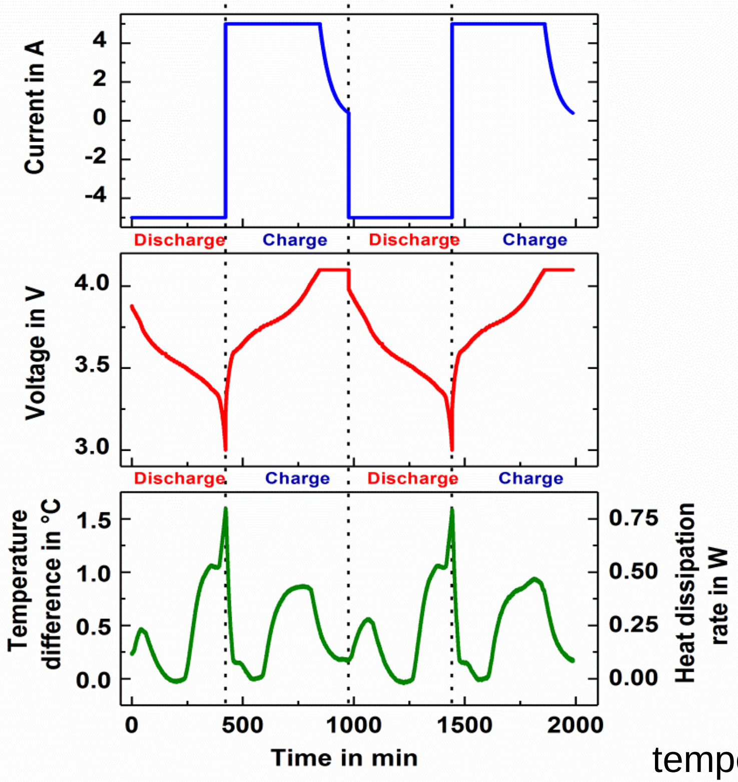
Ideal conditions

→ Single cell

Discharge parameter:
- method: constant current (CC)
- U_{min} = 3.0V
- I = 5A → C/8-rate

Charge parameter:
- method: constant current, constant voltage (CCCV)
- U_{max} = 4.1V
- I = 5A → C/8-rate
- I_{min} = 0.5A

→ after one electrochemical cycle the cell temperature reaches its initial value again



$$\left(\frac{\delta E}{\delta T}\right) < 0$$

temperature coefficient negative!

Methods for the determination of total generated heat

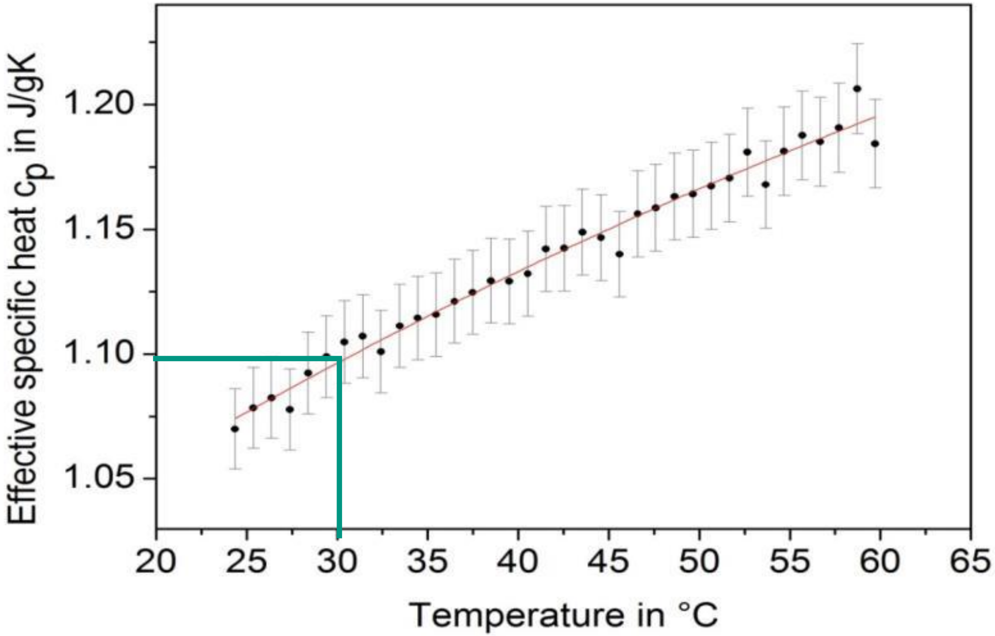
Heat generation of the cell during charging and discharging – Key data for thermal management and safety

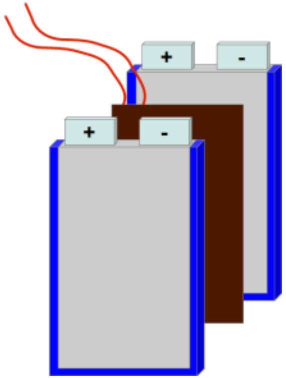
Conversion of thermal data (temperature, temperature rate) to heat (Joule) and power (Watt) with the aim of understanding of heat release to determine heat removal requirements for thermal management.

To be measured:

- **Cell effective specific heat capacity**
- **Heat transfer coefficient**
- **Reversible heat rate**
- **Irreversible heat rate**

Measurement of effective specific heat capacity c_p





Sandwich setup for pouch cells

Control of the current applied to the heater mat to ensure a constant heating rate

$$c_p = \frac{\Delta Q}{m \cdot \Delta T_{ad}} = \frac{\int U \cdot I \, dt}{m \cdot \Delta T_{ad}}$$

m: *Mass of the cell*

ΔT_{ad}: *Temperature difference under adiabatic conditions*

e.g. at 30 °C $\quad c_p = 1.095 \, {}^{J}/_{g \cdot K}$

Measurement of heat transfer coefficient h with heat flux sensors

gSKIN®-XP [1]
(10mm x 10mm)

Working principle of heat flux sensor

Tiny, serially connected semiconductor piles inside the sensor generate a voltage, which is proportional to the heat passing through the surface. The voltage is read out and depending on the sensor‘s sensitivity the results are converted into the heat flux [2].

Sensitivity:

$$S(T) = S_0 + (T - 22.5\,°C) \cdot S_C$$

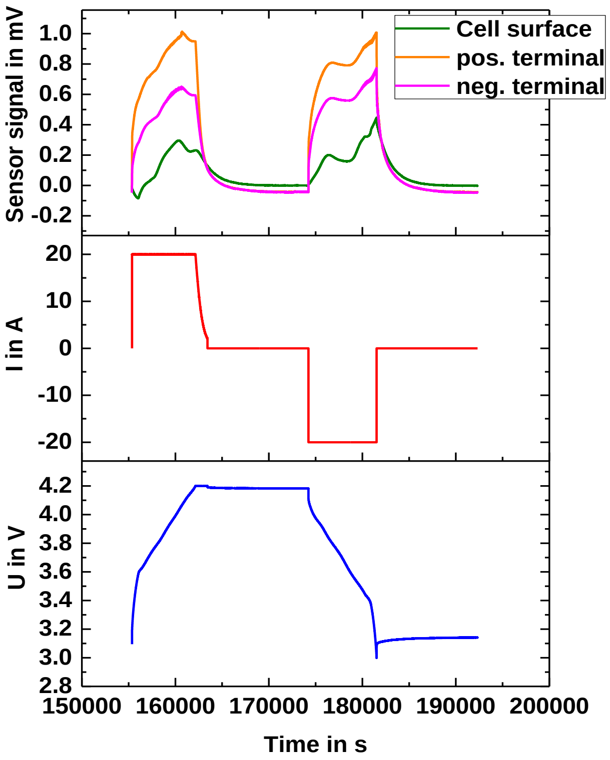
$$S_0 = 10.04 \frac{mV \cdot m^2}{W} \qquad S_C = 0.0049 \cdot \frac{mV \cdot m^2}{W \cdot °C}$$

Room temperature sensitivity *Temperature correction factor*

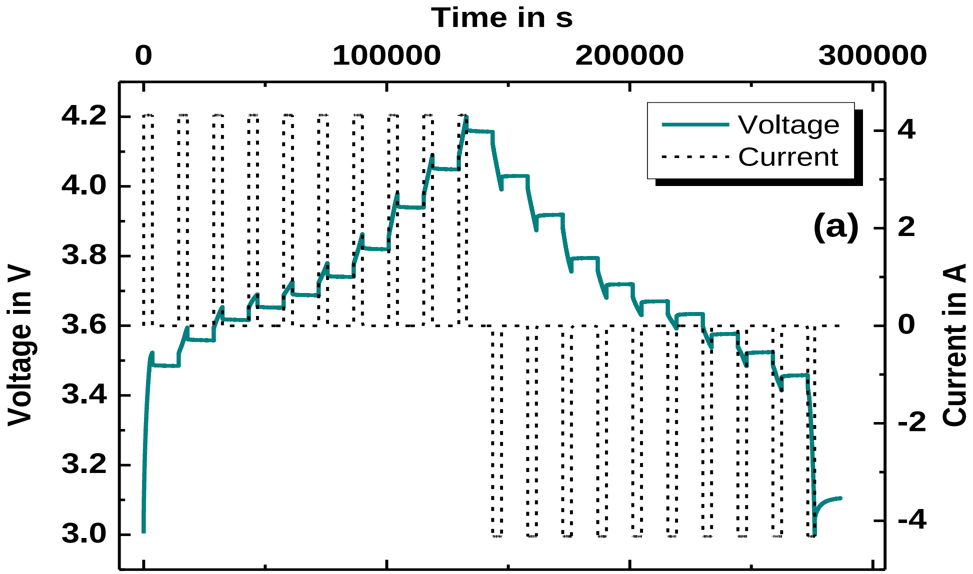
$$\Rightarrow h = \int \frac{U_{sensor}}{S(T)}\,dt \Bigg/ \int_0^t (T - T_C)\,dt$$

[1] http://shop.greenteg.com/shop/products-rd/gskin-xp/
[2] https://www.greenteg.com/faq-heat-flux-sensing/

Full cycle at 20A and 30°C

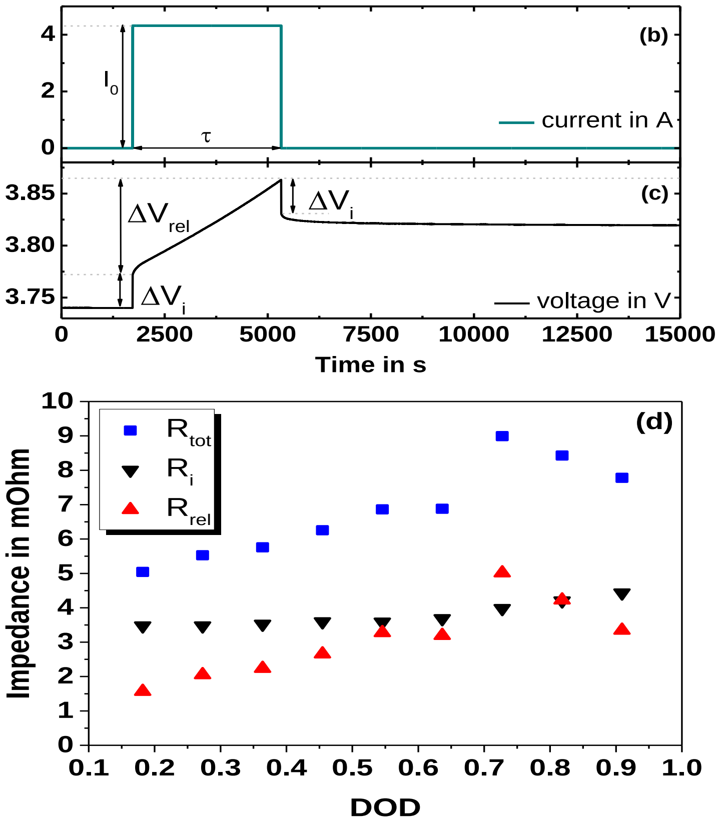


Irreversible heat measurement: Current interruption technique (CIT)



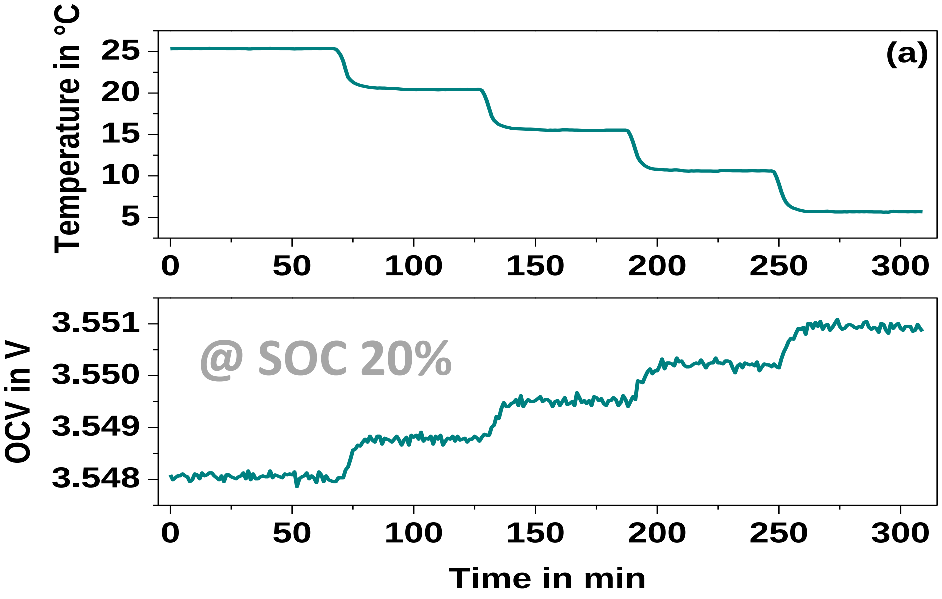
$$R_i = {}^{\Delta V_i}/_{I} \qquad \dot{Q}_{irrev} = -I^2 R_i$$

$$\dot{Q}_{irrev}(SOC = 0.6) = 1.4\,W$$

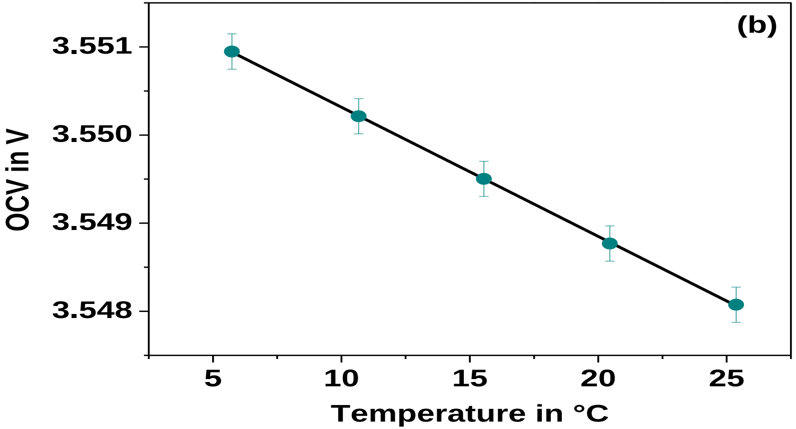


Current interruption technique (a), current vs. time plot (b) voltage vs. time plot (c) and resistance vs. depth of discharge (DOD) (d)

Reversible heat (entropy) measurement: Potentiometric method



$$\frac{dE_0}{dT} = -1.47 \cdot 10^{-4}\, {}^{V}\!/_{K}$$



$$\Delta S = nF\,\frac{dE_0}{dT} = -14.14\, {}^{J}\!/_{mol\cdot K}$$

n: number of electrons, F: Faraday constant 96485.3365 C/mol

Data for deriving entropy changes: (a) cell temperature and OCV (b) OCV vs. temperature plot

Comparison of the values for the generated heat determined by three different methods

1) Adiabatic Measurement

$$\dot{Q}_g = mc_p \frac{dT}{dt}$$

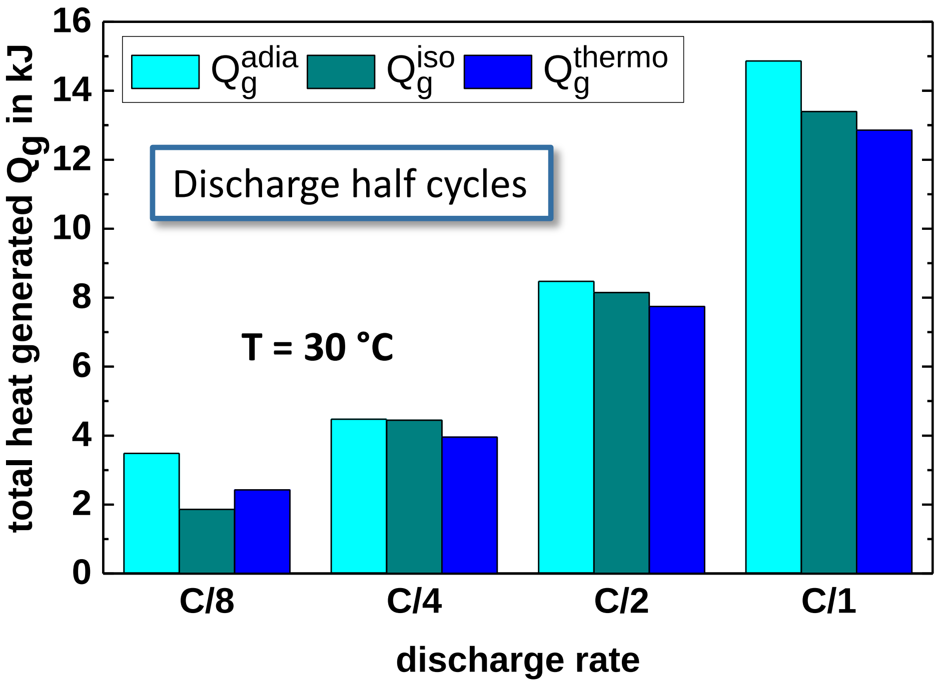
2) Isoperibolic Measurement

$$\dot{Q}_g = mc_p \frac{dT}{dt} + Ah \cdot (T_S - T_C)$$

3) Measurement of irreversible and reversible heat

$$\dot{Q}_g = -I(E_0 - E) - IT\frac{dE_0}{dT}$$

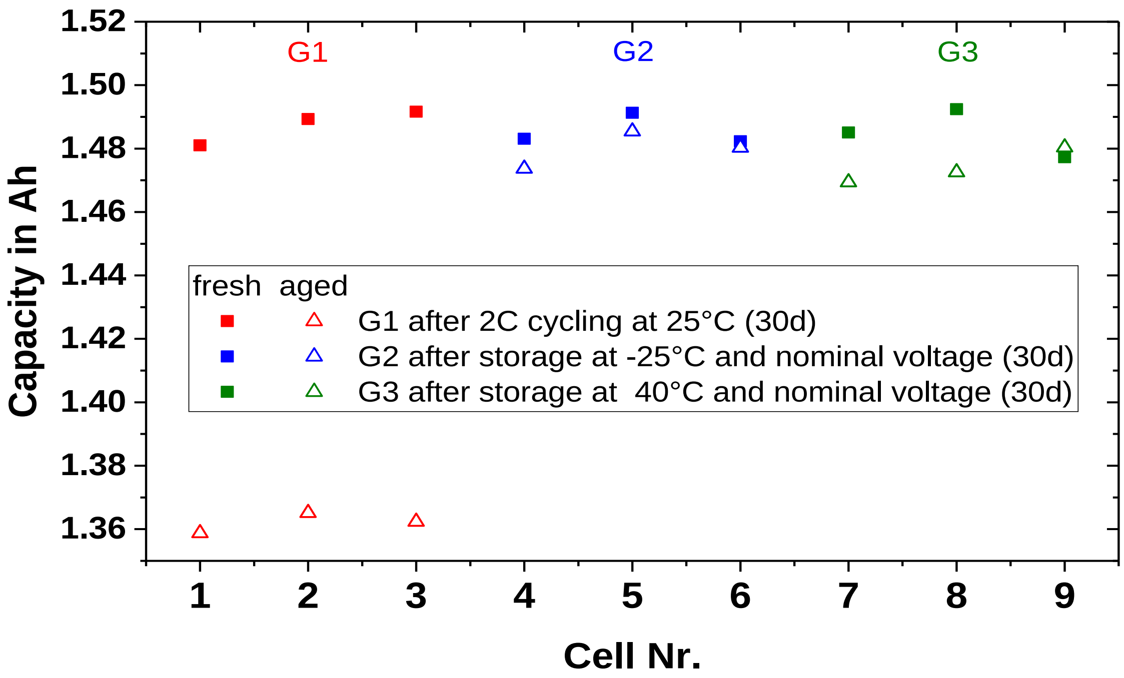
E_0: Open circuit voltage (OCV), E: cell potential



Conclusion: good agreement between the values determined by the different methods

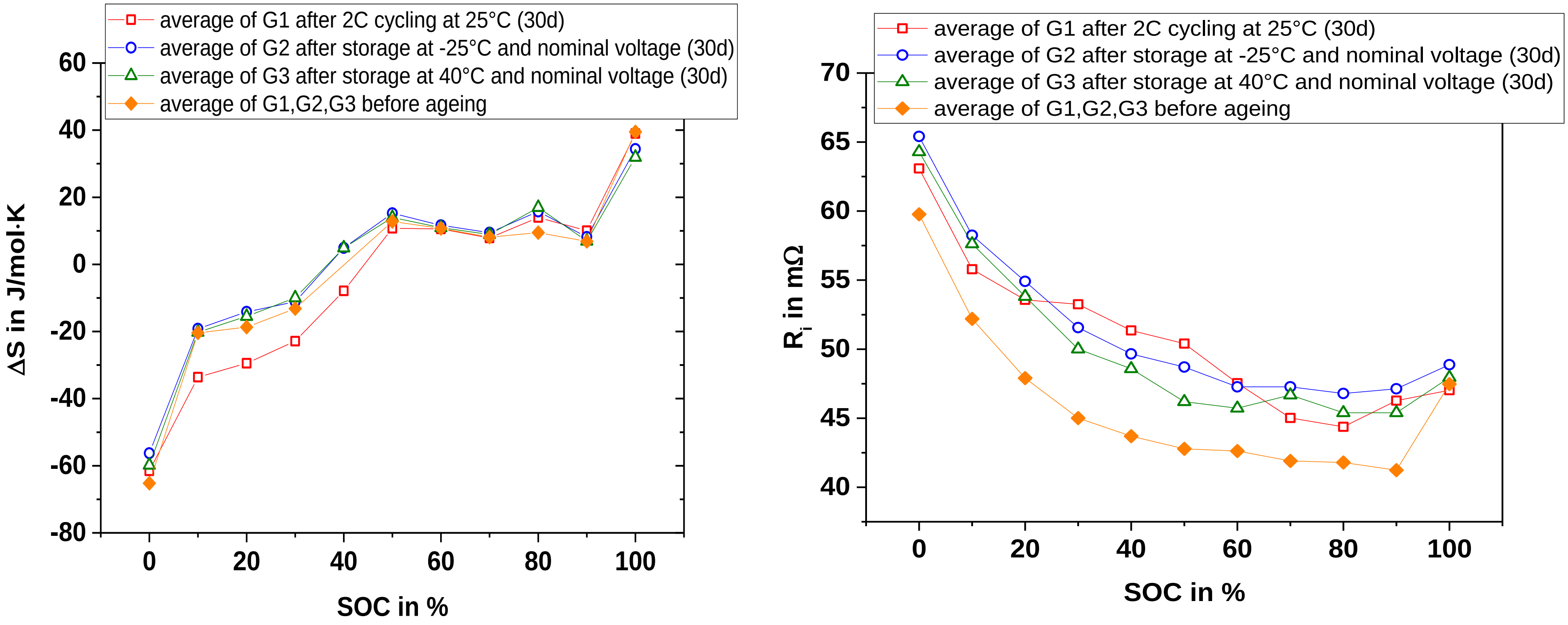
Source: E. Schuster, C. Ziebert, A. Melcher, M. Rohde, H.J. Seifert, J. Power Sources 268 (2015) 580-589

Influence of ageing phenomena on different modes of heat generation



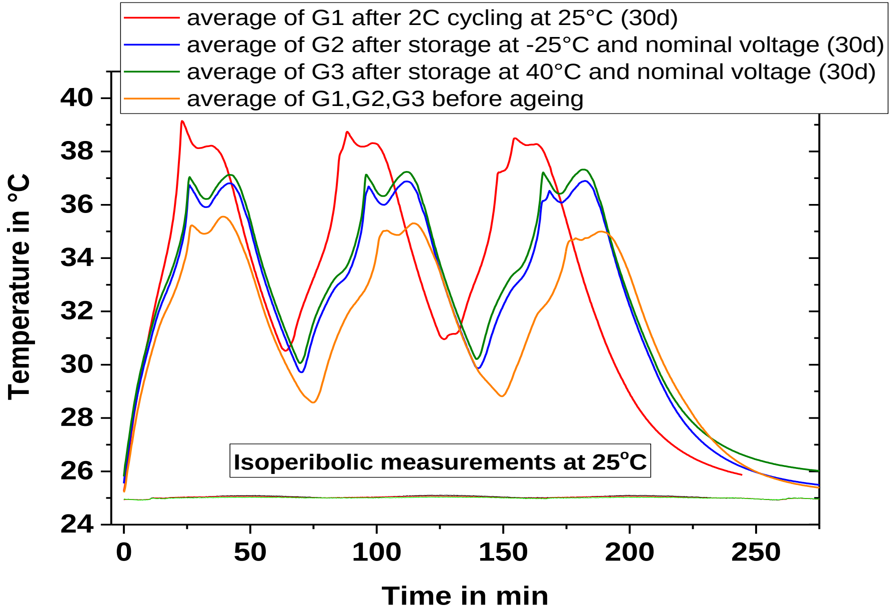
Comparison between fresh 18650 cells and the 3 cell groups (each consisting of 3 cells) after cyclic (G1) or calendaric (G2, G3) ageing for 30d.

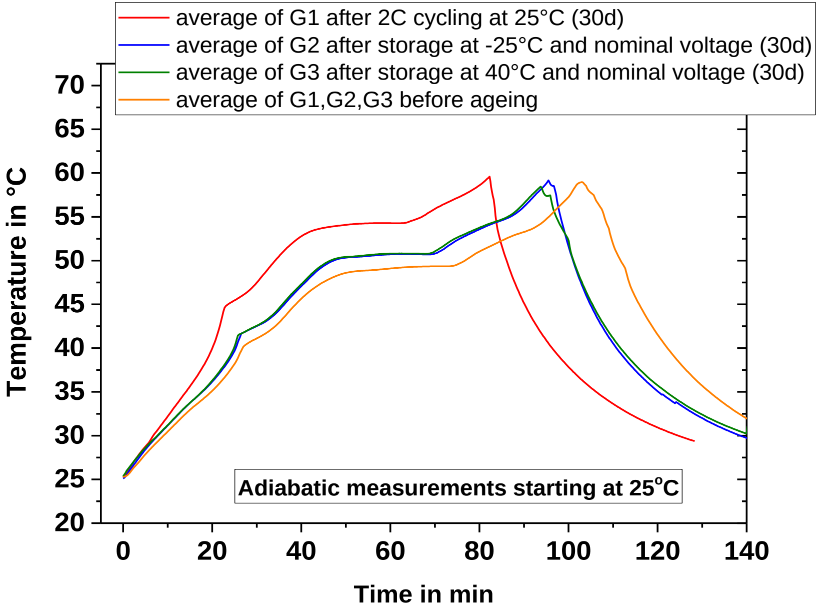
Influence of ageing phenomena on different modes of heat generation



Comparison between fresh 18650 cells and the cell groups (each consisting of 3 cells) after cyclic (G1) or calendaric (G2, G3) ageing for 30d: (a) Entropy curves (b) Inner resistances as function of SOC.

Influence of ageing phenomena on different modes of heat generation





Comparison between fresh 18650 cells and the cell groups (each consisting of 3 cells) after cyclic (G1) or calendaric (G2, G3) ageing for 30d: (a) Isoperibolic cycling (b) Adiabatic cycling in the ARC.

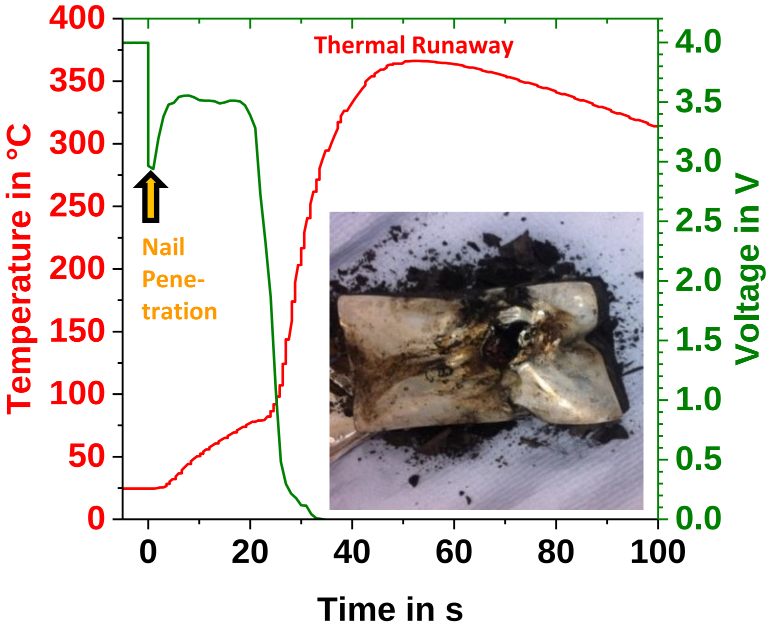
Conclusion: Recording of temperature profile can be used as a "fingerprint" for the SOH and as a fast and reliable method for the characterization of aging processes

Safety tests

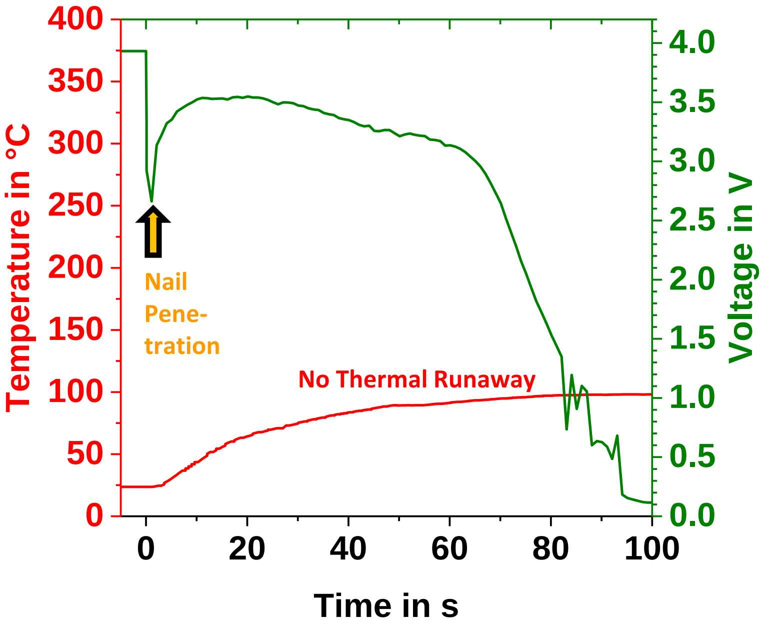
a) Mechanical abuse: Nail penetration test

Comparison of different SOC

SOC 80



SOC 70



Nail penetration test in the ARC on a 2.5 Ah pouch cell

Safety tests

a) Mechanical abuse: Nail penetration test

Comparison of different SOC

SOC 80

T_{max} = 366.24 °C T_0 = 24.60 °C

ΔH = 17.08 kJ

SOC 70

T_{max} = 98.13 °C T_0 = 23.65 °C

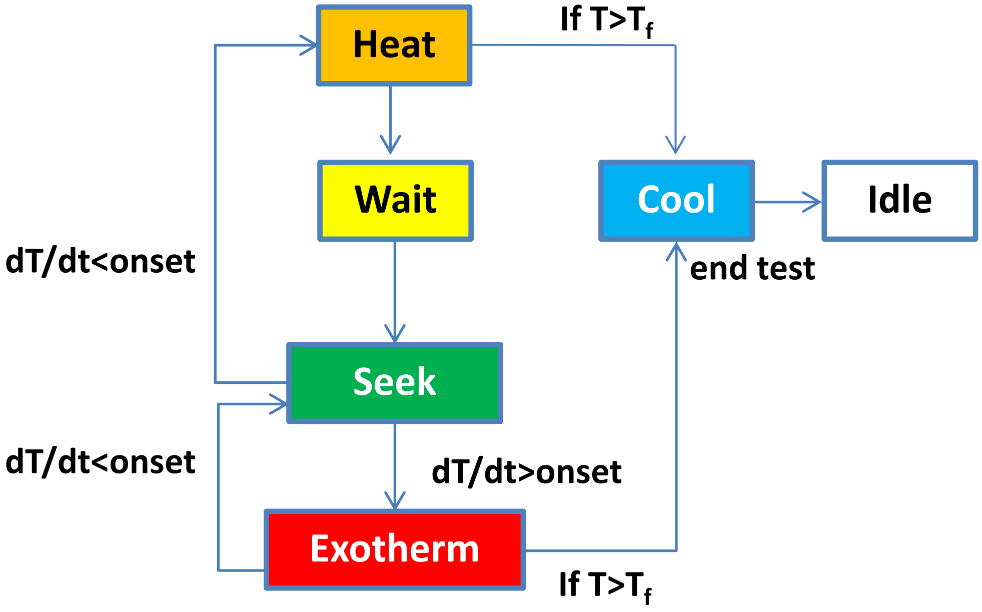
ΔH = 3.73 kJ

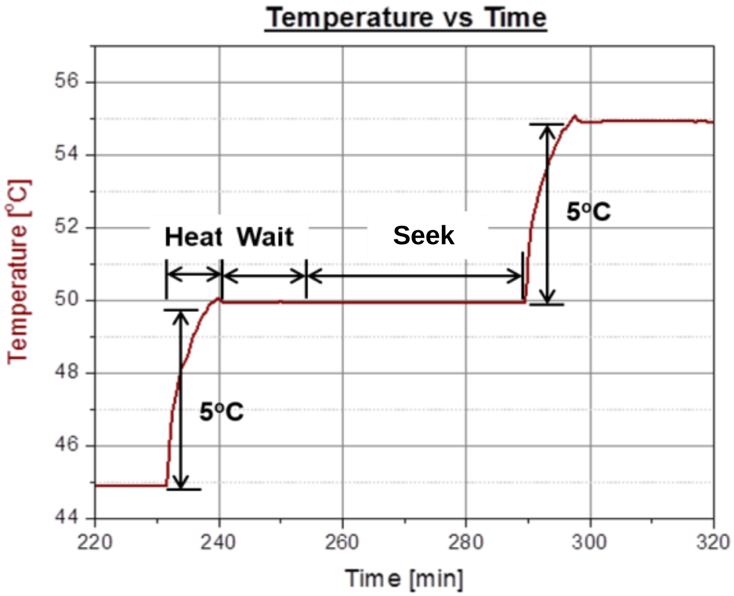
Heat of reaction $\Delta H = m \cdot c_p \cdot \Delta T$

$c_p = 1.0$ J/g K $m = 50.0$ g

Nail penetration test in the ARC on a 2.5 Ah pouch cell

b) Thermal Abuse: Heat-Wait-Seek(HWS) Method

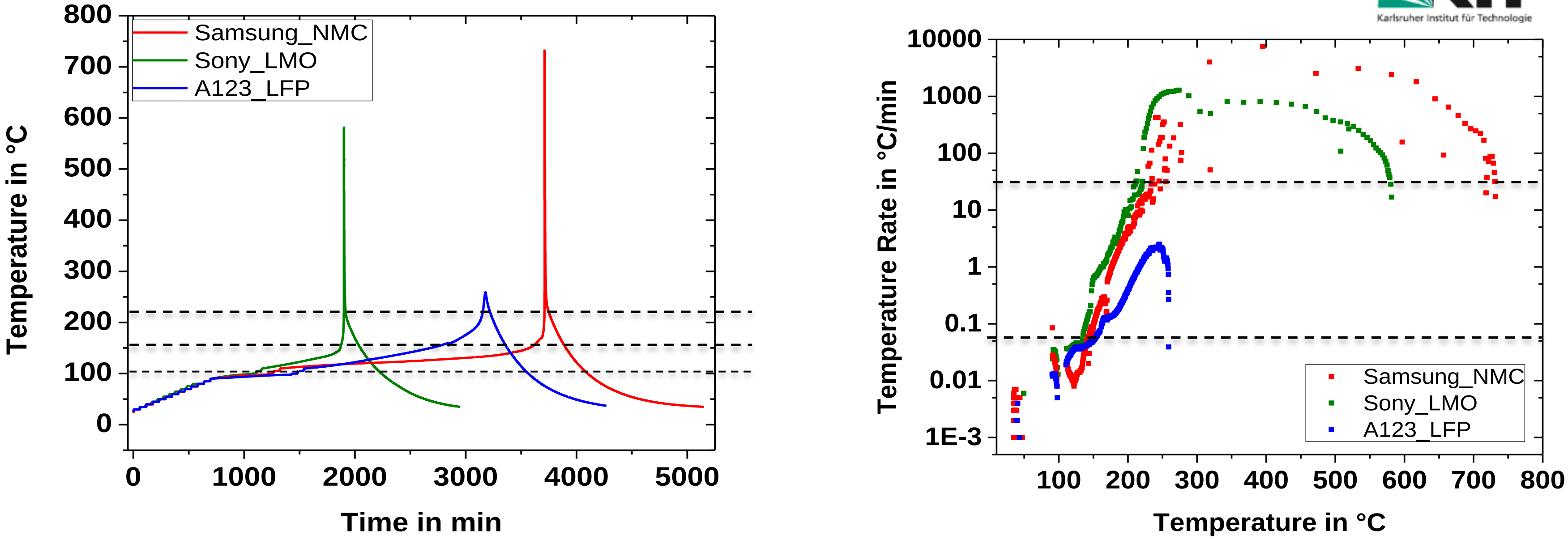




Example of a Heat-Wait-Seek step

C. Ziebert, A. Melcher, B. Lei, W.J. Zhao, M. Rohde, H.J. Seifert, Electrochemical-thermal characterization and thermal modeling for batteries, in: L.M. Rodriguez, N. Omar, Eds., EMERGING NANOTECHNOLOGIES IN RECHARGABLE ENERGY STORAGE SYSTEMS, Elsevier Inc. 2017, ISBN 978032342977.

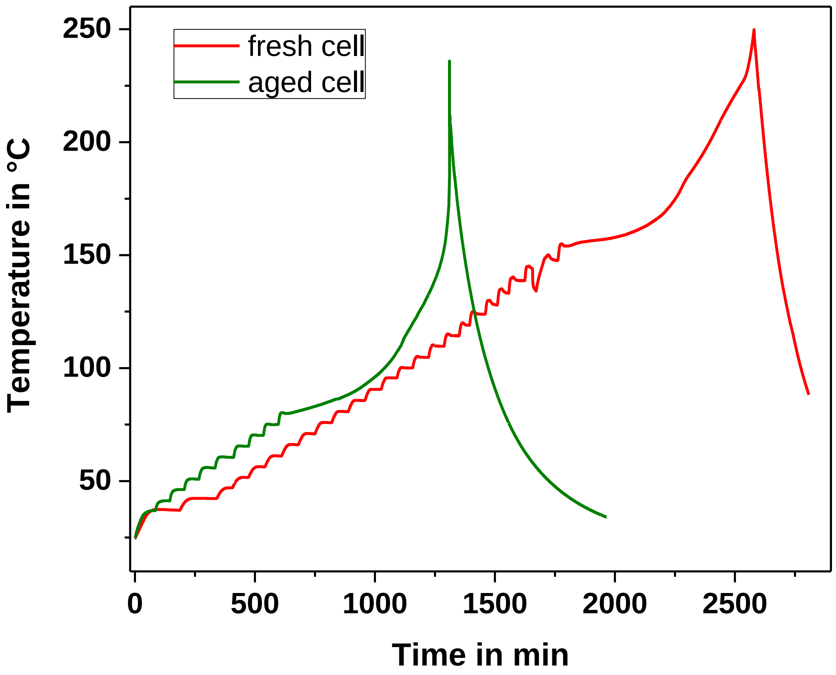
Thermal Runaway: 18650 cells with different cathode materials

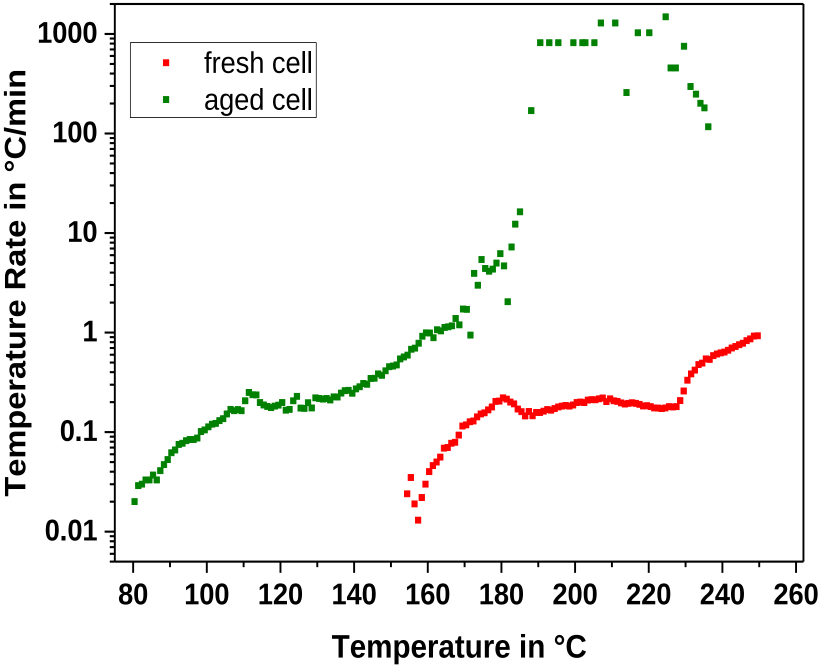


- 80<T<130°C: low rate reaction, 0.02 - 0.05 °C/min: exothermic decomposition of the SEI
- 130<T<200°C: medium rate reaction, 0.05 - 25 °C/min: solvent reaction, exothermic reaction between embedded Li ions and electrolyte => reduction of electrolyte at negative electrode
- T > 200°C: high rate reaction, higher than 25 °C/min: Exothermic reaction between active positive material and electrolyte at positive electrode => rapid generation of oxygen

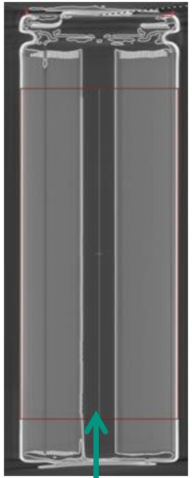
Study of ageing effects of PHEV1 cells by thermal runaway tests

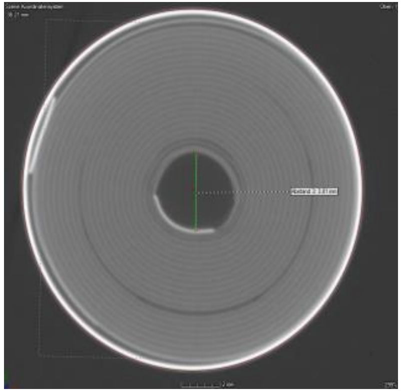
Karlsruher Institut für Technologie



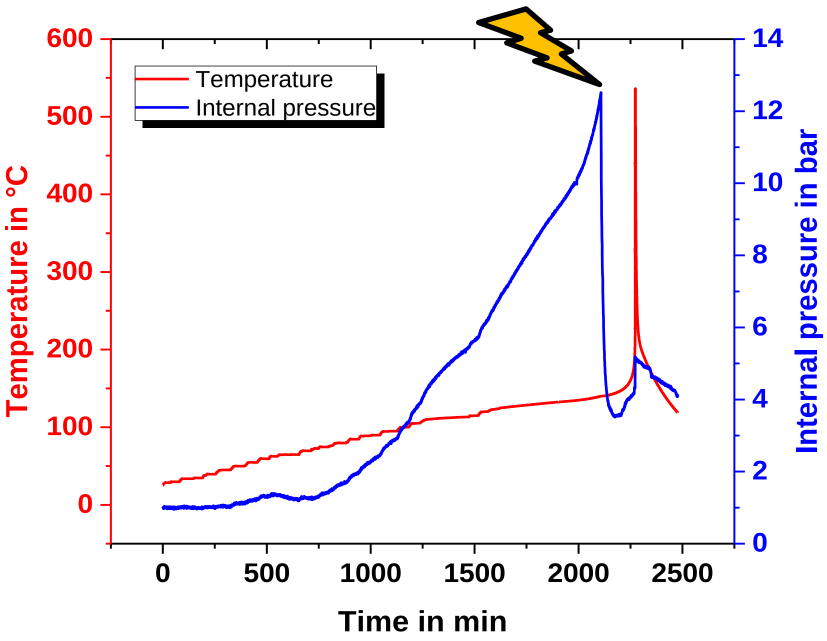


Development of internal pressure measurement methods for 18650 cells





Pressure line (Ø 1.5 mm)

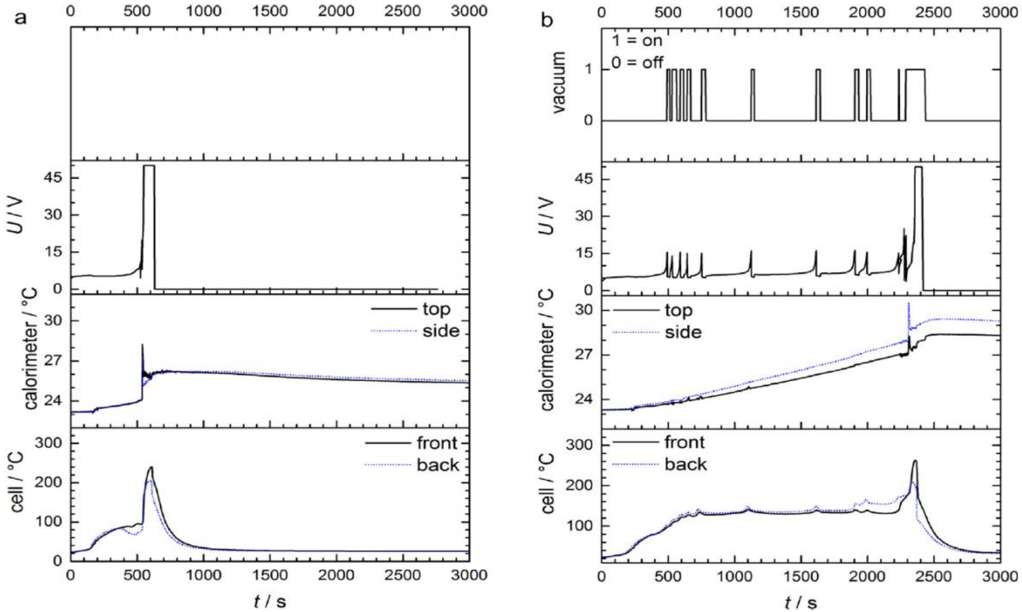


Internal pressure could be used in BMS for early prediction of processes leading to thermal runaway

B. Lei, W. Zhao, C. Ziebert, A. Melcher, M. Rohde, H.J. Seifert, Batteries 2017, 3, 14, doi:10.3390/batteries3020014.

c) Electrical abuse: Overcharge test

Cell tests during thermal runaway caused by overcharging at 10 C. (a) Overcharging experiment without prevention. (b) During thermal runaway vacuum is applied by a vacuum pump.

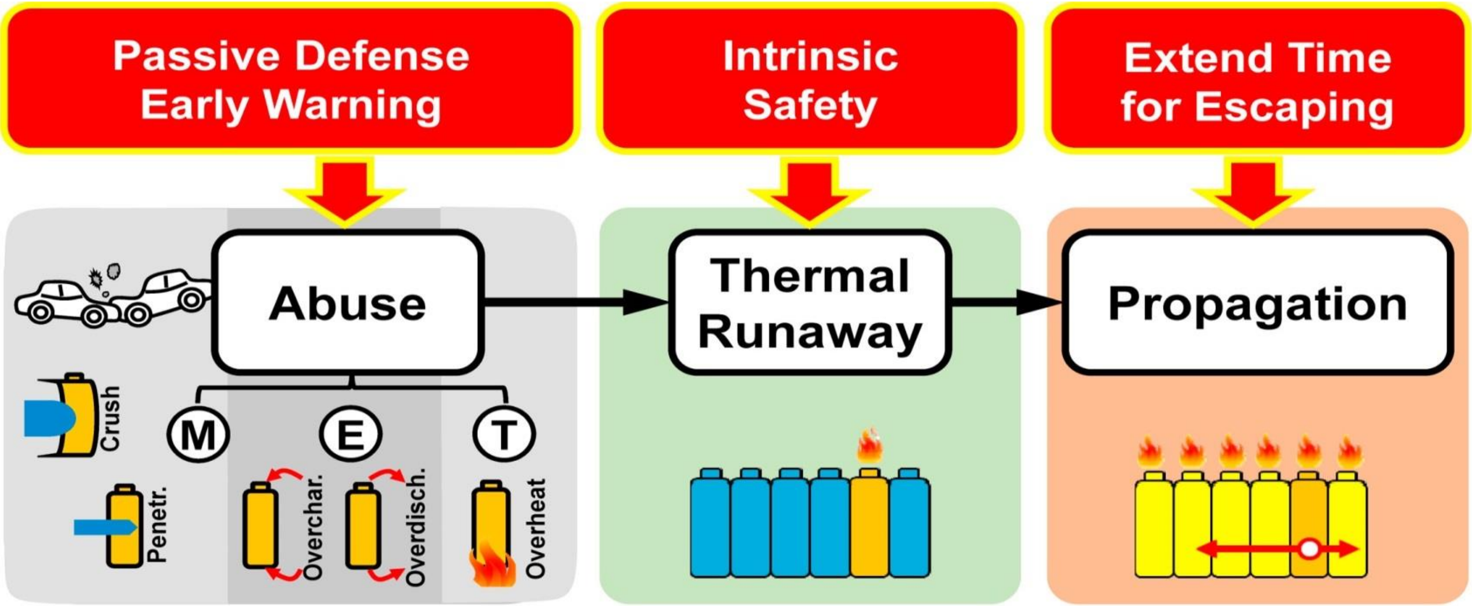


Overcharging measurement inside an accelerating rate calorimeter with 264 mAh pouch cells without (a) and with vacuum control (b). Depicted from bottom to top are cell temperatures for both sides, calorimeter temperature (top and side temperature), the cell voltage and the vacuum control.

A. Hofmann, N. Uhlmann, C. Ziebert, O. Wiegand, A. Schmidt, Th. Hanemann, Applied Thermal Engineering, 124 (2017) 539-544.

Conclusion: Pressure reduction of pouch cells as safety measure for thermal runaway prevention

The three-level strategy of reducing the hazard of thermal runaway



<u>Step 1 - BMS</u>

Detection of mechanical, thermal, electrical abuse

<u>Step 2 – Cell :</u>

Venting, CID, PTC

<u>Step 3 – Pack</u>

Passive propagation prevention

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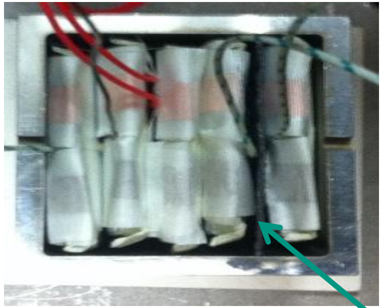
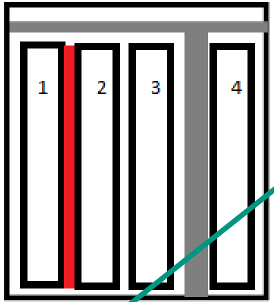
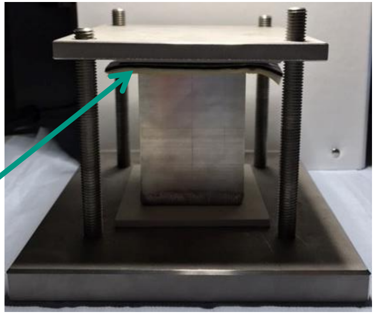
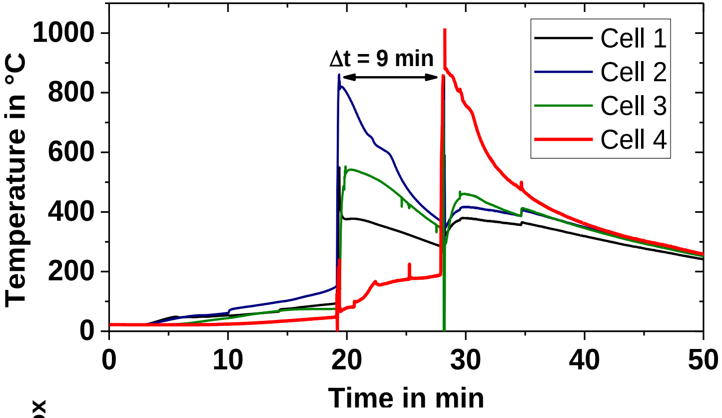
Material qualification for passive propagation prevention

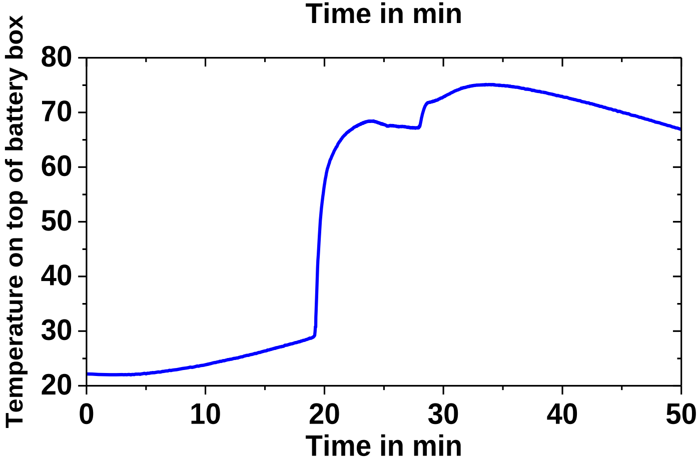






Gray: protective material for cell 4 and lid of battery box
Red: heater mat for thermal runaway initiation

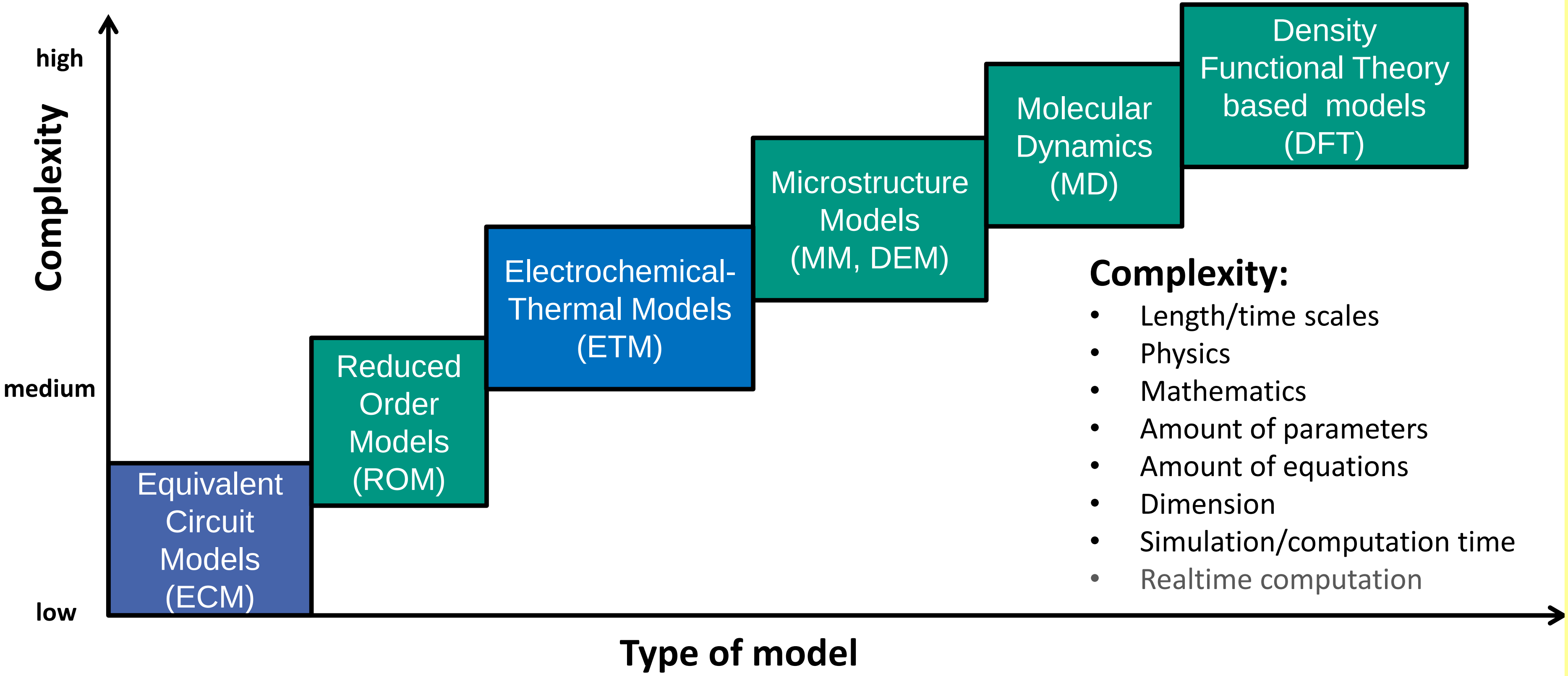




Optimized Multilayer: HKO-Defensor ML 14

- **Extended time for propagation: 9 min**
- **Improved heat protection: temperature on top of battery box < 80 °C during thermal runaway**

Modelling and Simulation

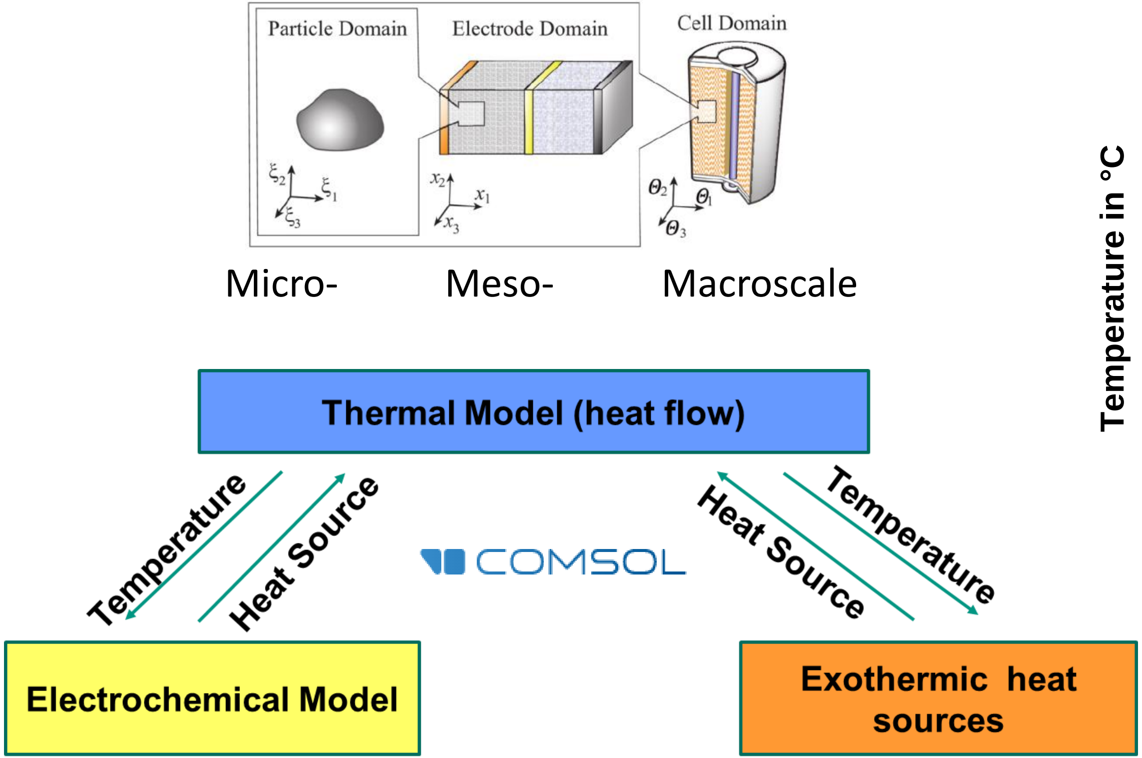


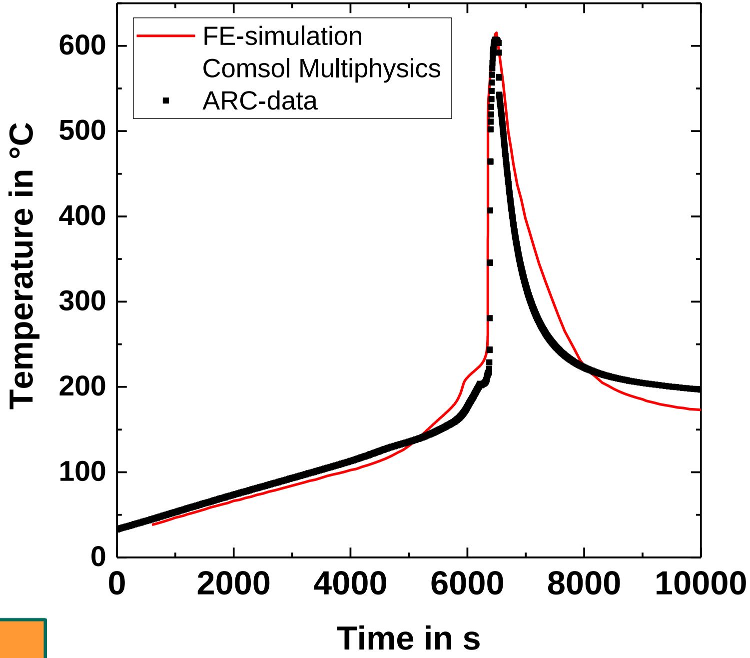
Complexity:

- Length/time scales
- Physics
- Mathematics
- Amount of parameters
- Amount of equations
- Dimension
- Simulation/computation time
- Realtime computation

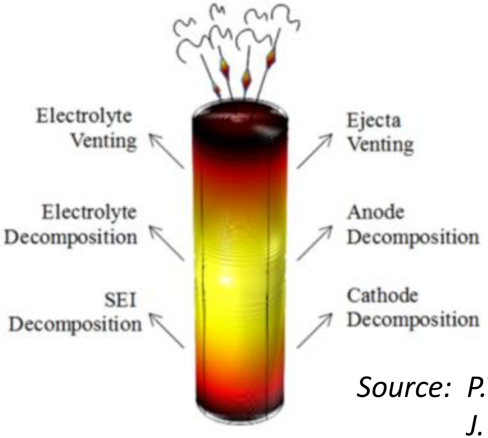
Comparison of experimental and simulation results for 18650 cells

Thermal runaway (MSMD with Arrhenius-type exothermal extensions)

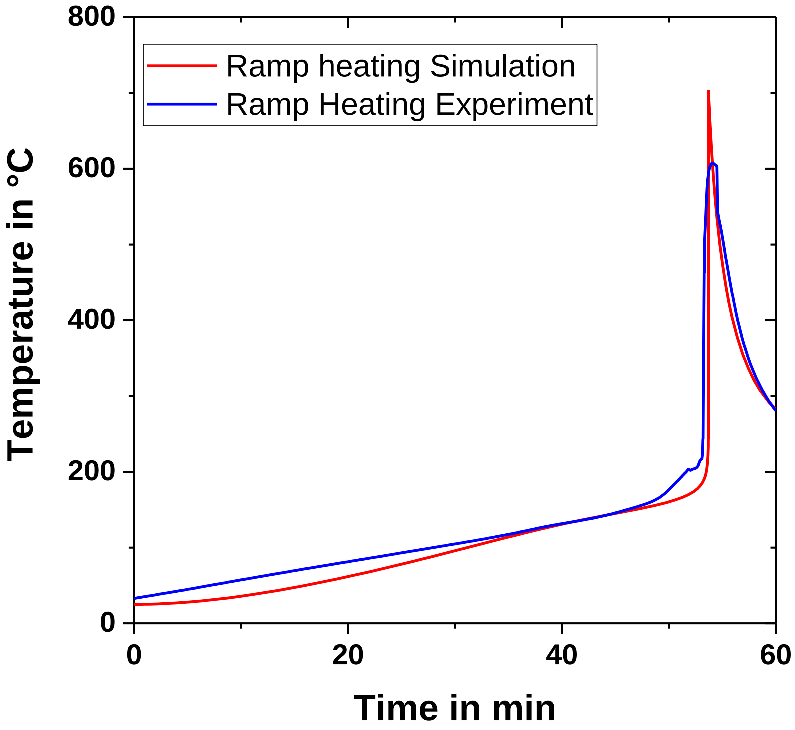




Electrochemical-Thermal Model: Lumped Matlab ODE model for ramp heating with venting



*Source: P.T. Coman, S. Rayman, R. E. White, J. of Power Sources **307** (2016) 56.*



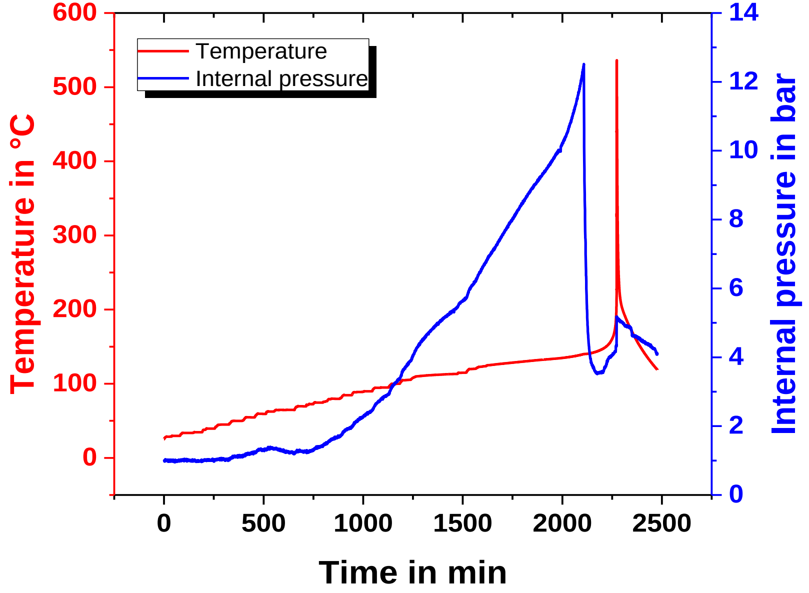
a model for ramp heating with ODEs representing:

- the decomposition rates
- the energy balance
- the ideal gas flow equations
- the burst condition for the trigger pressure
- the partial ejection of the jelly roll

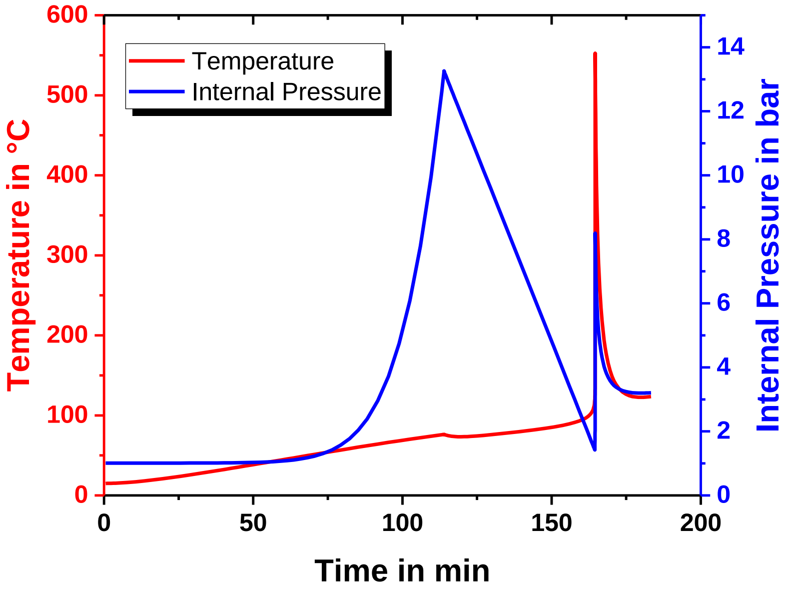
Comparison of experimental and simulation results for 18650 cells

Thermal runaway including internal pressure evolution

Experiment (HWS)



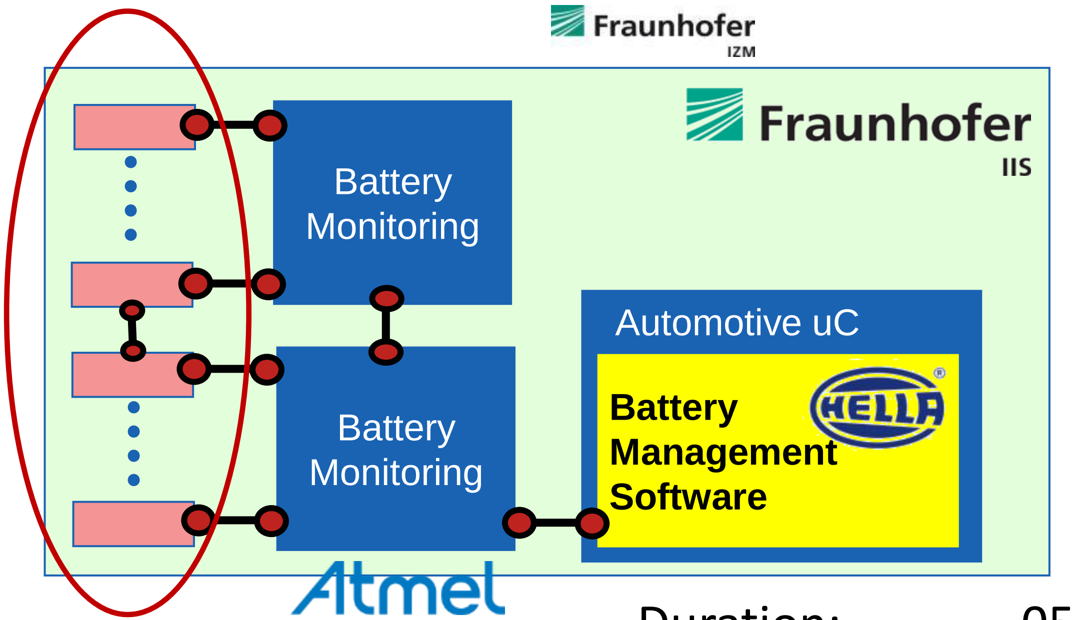
Simulation (Ramp Heating)



Equivalent Circuit Model

IKEBA Project

Integrated Components and Integrated Design of Energy Efficient Battery Systems



ECM Cell Modelling

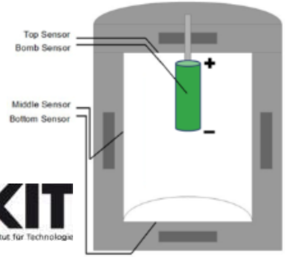
5 cooperating partners

Duration:	05/2013-07/2016
Budget:	7 Million Euro

Modelling Workflow

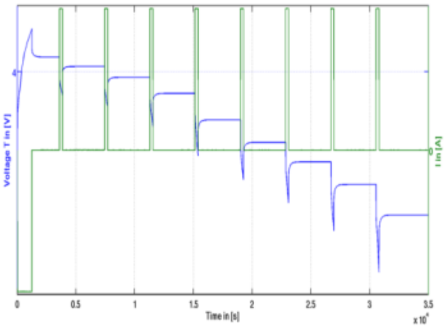
Cell Model Parametrization

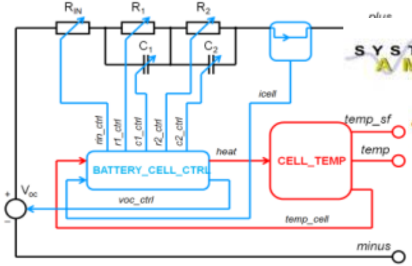
Cell Model Implementation



6s1p Pack

Measurements in battery calorimeters on cell and pack





Battery model in BMS design platform

Cell Model Optimization

Lookup-Table (LUT): 25°C

SOC/%	R_0/mΩ	R_1/mΩ	R_2/mΩ	τ_1/s	τ_2/s
0	55.0	1.00	14.2	15.1	724.0
5	50.0	1.16	13.0	16.5	624.4
10	46.9	1.31	11.6	20.2	524.6
...	...	...	...	...	...
70	42.1	2.03	6.7	32.4	226.6
75	42.0	1.68	7.5	28.2	280.2
...	...	...	...	...	...
100	43.3	2.00	4.5	40.8	200.3

Vary the LUTs system.

Detail of 31 varied LUTs

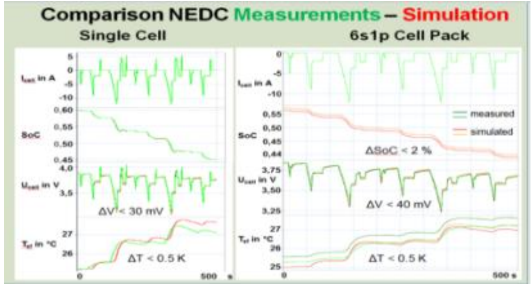
	SOC/%	R_0/mΩ	R_1/mΩ	R_2/mΩ	τ_1/s	τ_2/s
	...	...	...	...	...	...
original	70	42.1	2.03	6.7	32.4	226.6
original	75	42.0	1.68	7.5	28.2	280.2
	...	...	...	...	...	...
var1	70	46.3	2.03	6.7	32.4	226.6
var1	75	42.0	1.68	7.5	28.2	280.2
	...	...	...	...	...	...
var9	70	42.1	2.23	6.7	32.4	226.6
var9	75	42.0	1.85	7.5	28.2	280.2

Simulate all varied LUTs

Determine the best LUT

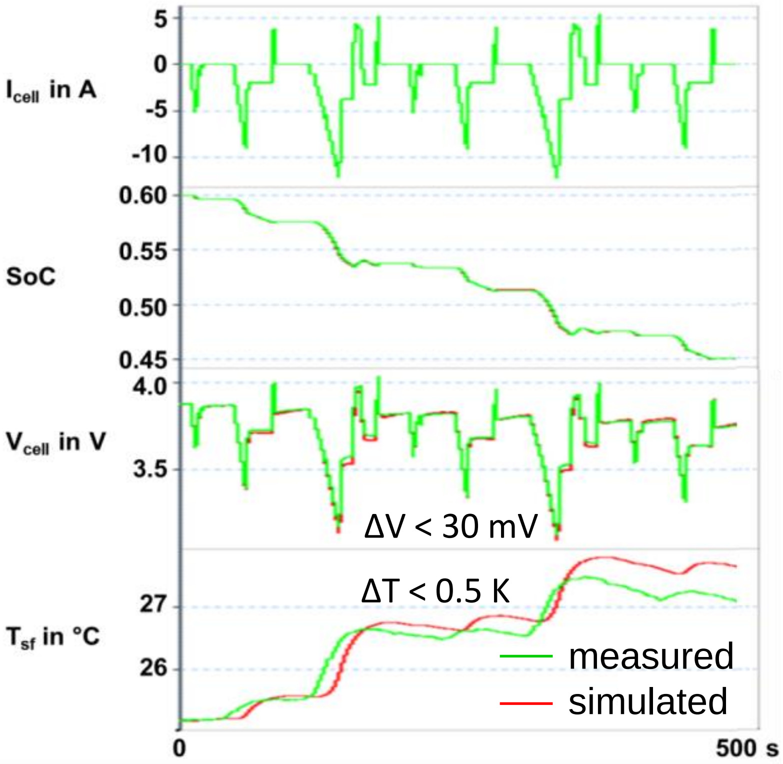
BMS Demonstrator

Cell Model Validation

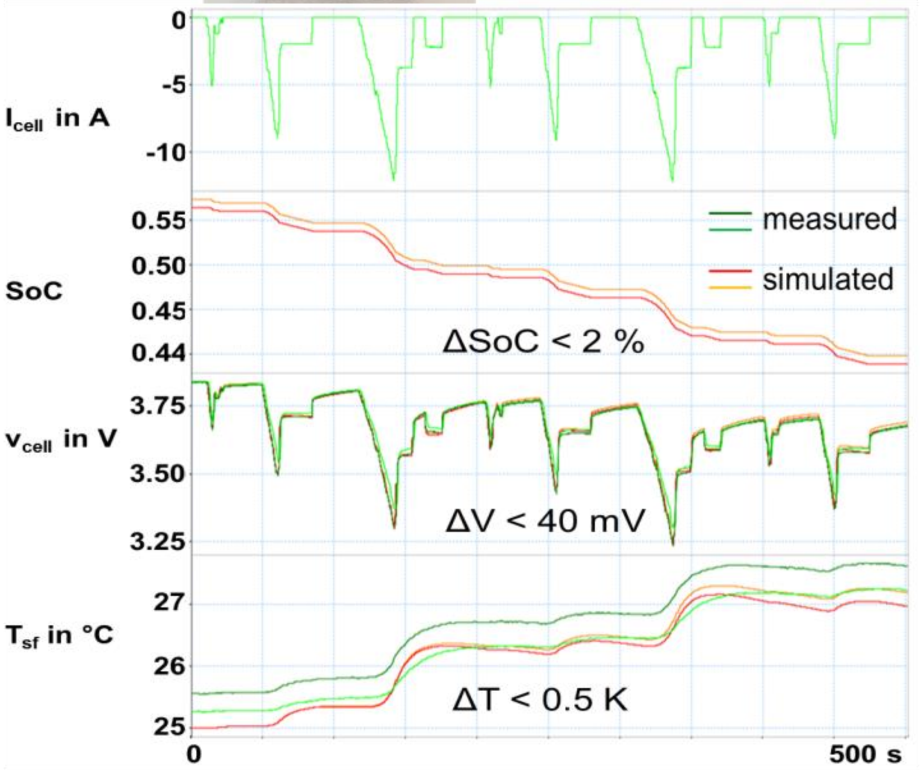


Comparison of measurements and simulations by using current profile based on NEDC

Single Cell



6s1p Battery Pack



NEDC (New European Driving Cycle)

Summary: Possible measurements with a battery calorimeter

Normal conditions of use

- Isoperibolic or adiabatic measurement

For each:

- ➢ Measurement of temperature curve and temperature distribution during cycling (full cycles, or application-specific load profiles), ageing studies
- ➢ Determination of the generated heat, Separation of heat in reversible and irreversible parts

Abuse conditions

- Thermal abuse: Heat-wait-seek test, ramp heating test, thermal propagation test
- External short circuit, nail penetration test
- Overcharge, deep discharge

For each:

- ➢ Temperature measurement
- ➢ External or internal pressure measurement
- ➢ Gas collection, Post Mortem Analysis, Ageing studies

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→ Important data for BMS, TMS and safety

Thank You
For Your Kind Attention

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Supervised by

This work has been partially funded by the Federal Ministry for Education and Research (BMBF) within the framework "IKT 2020 Research for Innovations" under the grant 16N12515 and is supervised by the Project Management Agency VDI|VDE|IT.

Additional funding by the German Research Foundation priority programme SPP1473 WeNDeLIB is gratefully acknowledged.