Introduction to Battery Thermal Runaway Testing @ VIRTUAL VEHICLE

Alex Thaler representing the work from Dr. Christiane Essl
Virtual Vehicle Research GmbH, Department E / Team Lead Battery Safety

Federal Ministry Republic of Austria Climate Action, Environment, Energy, Mobility, Innovation and Technology
Federal Ministry Republic of Austria Digital and Economic Affairs
FFG Promoting Innovation.
Das Land Steiermark
SFG

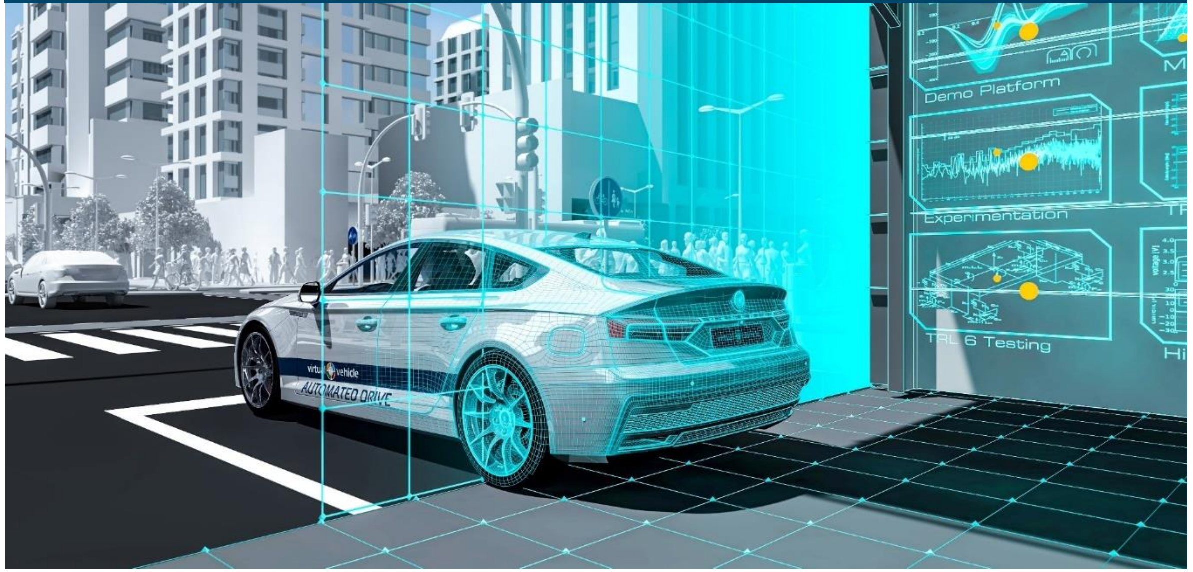
Agenda

- ❑ **Short introduction: VIRTUAL VEHICLE Research**
- ❑ **Some initial topics regarding (automotive) battery technology**
- ❑ **Research on battery safety- on overview**
- ❑ **Conclusion: Safety Summary- influencing factors**

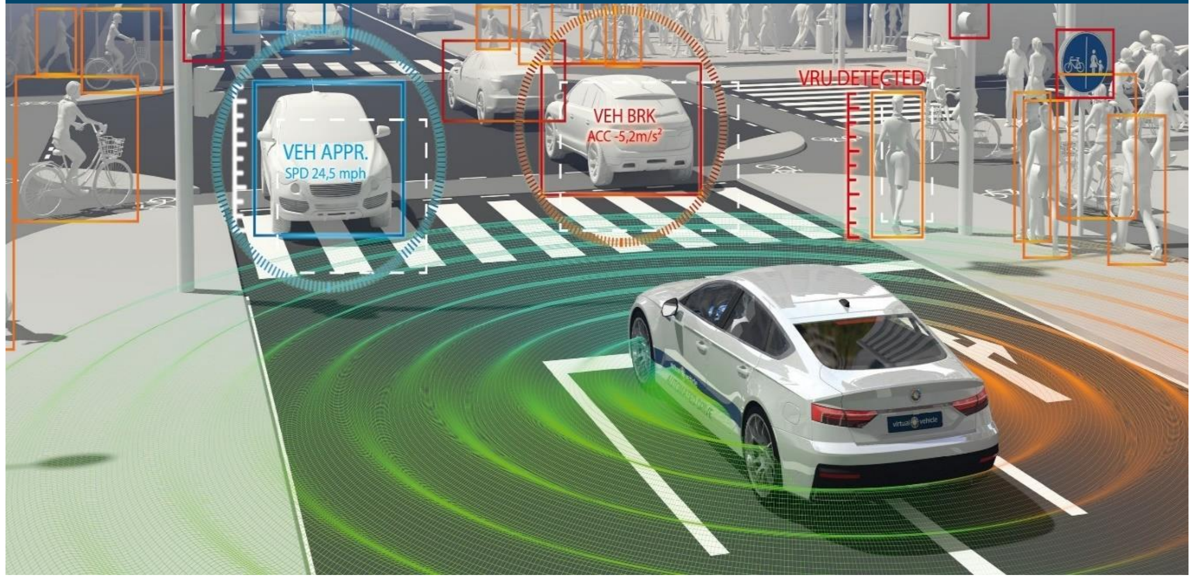
Fields of Expertise - General

GREEN MOBILITY & TRANSPORT

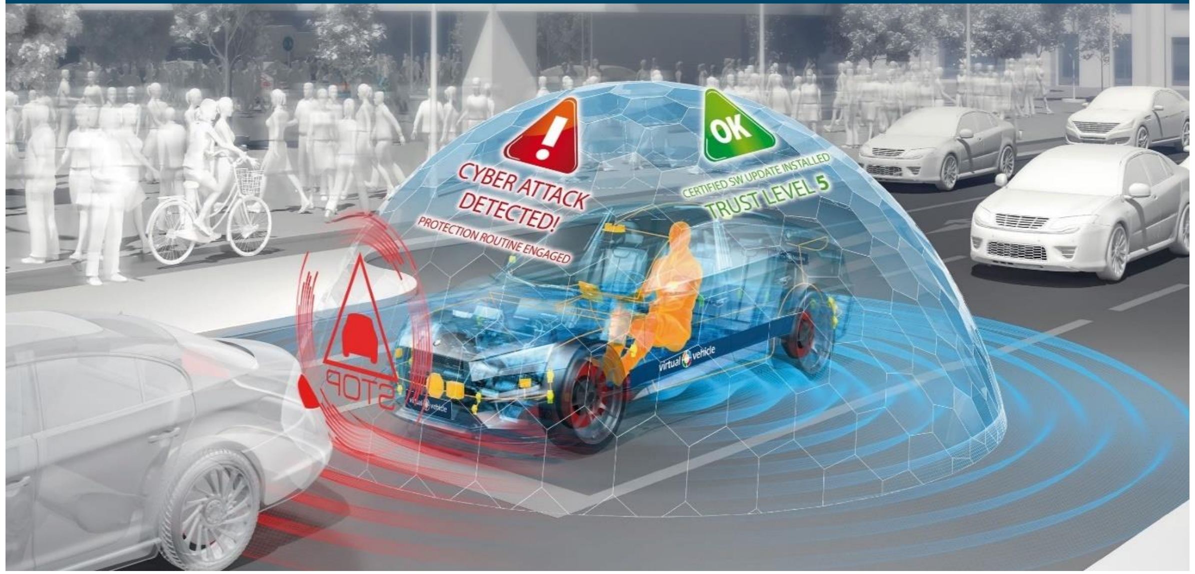
VIRTUAL VALIDATION & HOMOLOGATION



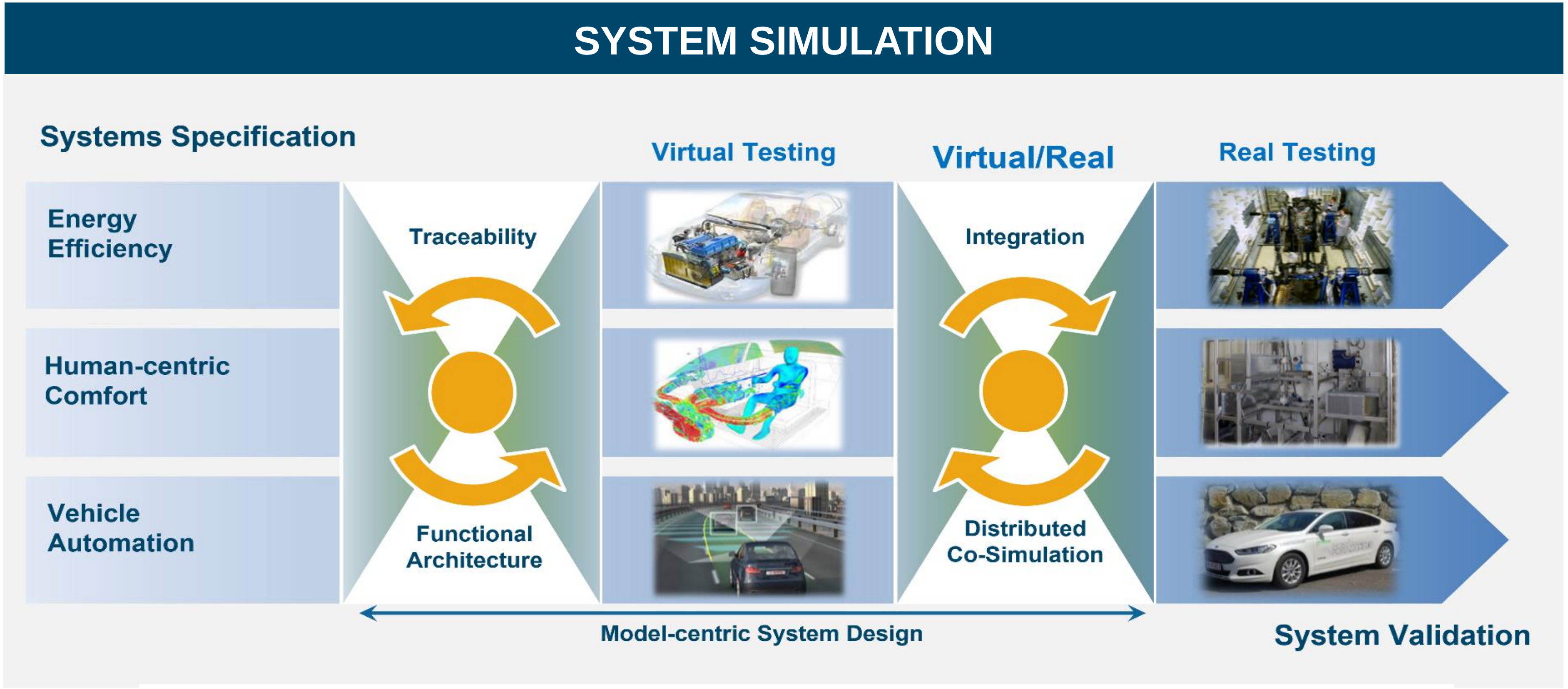
AUTOMATED/ADAS SYSTEMS



SAFETY & SECURITY



USP: System-Simulation in different Domains



Domains

MOBILITY

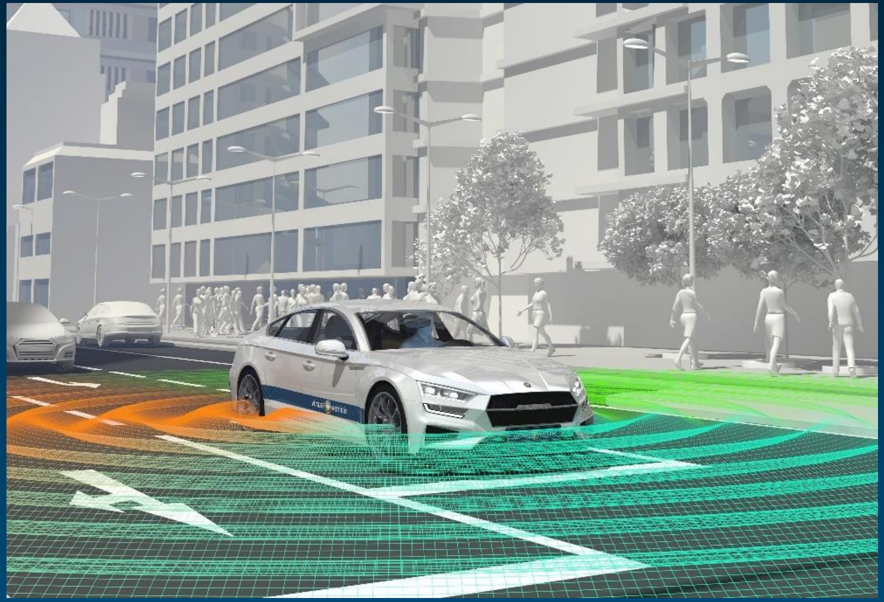
ROBOTICS

LOGISTICS

ENERGY

HEALTHCARE

A bridge between science and industry

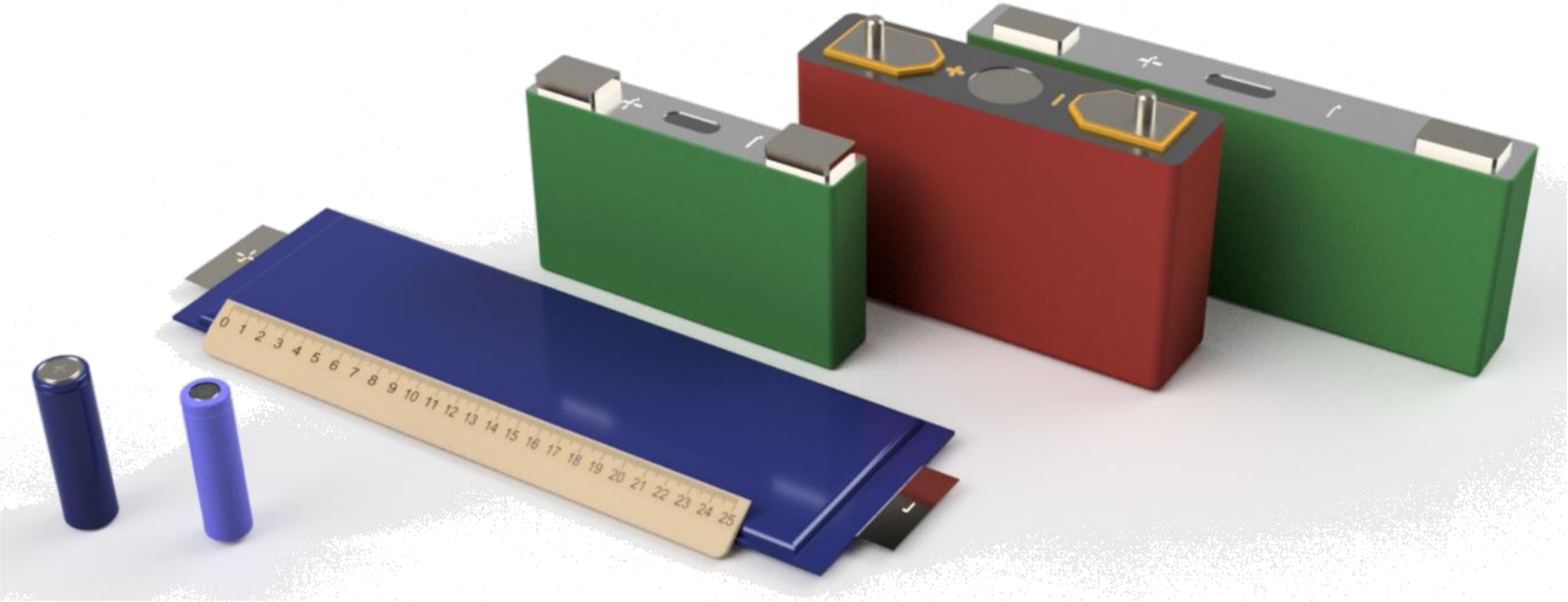
COMET K2	FUNDED PROJECTS	CONTRACT WORK
		
▪ Digital Mobility ▪ Long term co-operative research ▪ Leveraging of invest	▪ 40+ ongoing EU Projects ▪ 90+ successfully completed ▪ International visibility and reputation (Initiator, Coordinator)	▪ Research & Development ▪ Test Bed & Demonstrators ▪ Industry agreements

Comprehensive knowledge of

~320 in-house experts

Initial topics, Battery Trends

Cell Types



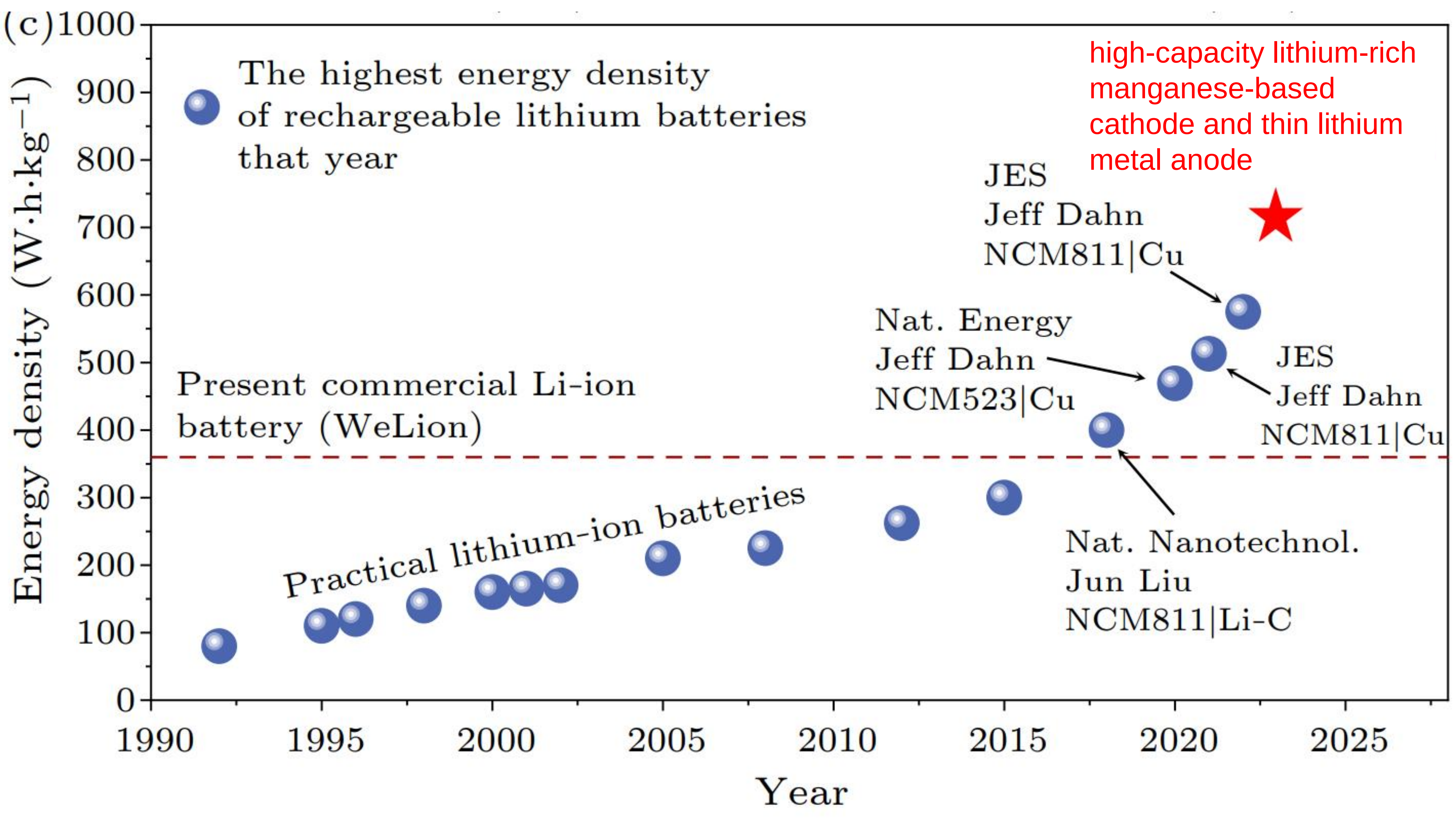
Opening a Sample Pouch Cell

Why Lithium-Ion technology?

		NiCd	NiMH	Lithium Ion
Specific energy [Wh/kg]	Cell	30 – 50	35 - 40	120 - 300
	System	25 -40	30 - 40	70 - 140
Energy density [Wh/l]	Cell	55 – 70	75 - 80	350 - 750
	System	45 – 60	65 - 70	75 - 175
Specific power [W/kg]	Cell	80 – 300	300 - 450	450 - 2200
	System	70– 250	250 - 400	300 - 550
Power density [W/l]	Cell	110 – 600	600 - 900	900 - 4000
	System	95 – 500	500 -750	300 - 600
Lifetime	FCE (Full Cycle Equivalent)	3000	3000	> 5000
	Calendar lifetime [a]	20	15	15
Operating temperature [°C]		- 50 - +60	-20 - +70	0 - +60 °C charge -20 - +60 °C disch..
Energy efficiency [%]		70 – 80	75 – 85	> 95
Price [€/kWh]	Cell	280 - 700	500 – 800	120 - 350
	System	375 - 900	650 - 1050	200 - 1000

Source: Varta Innovation

Development on Cell level- Gravimetric Energy Density

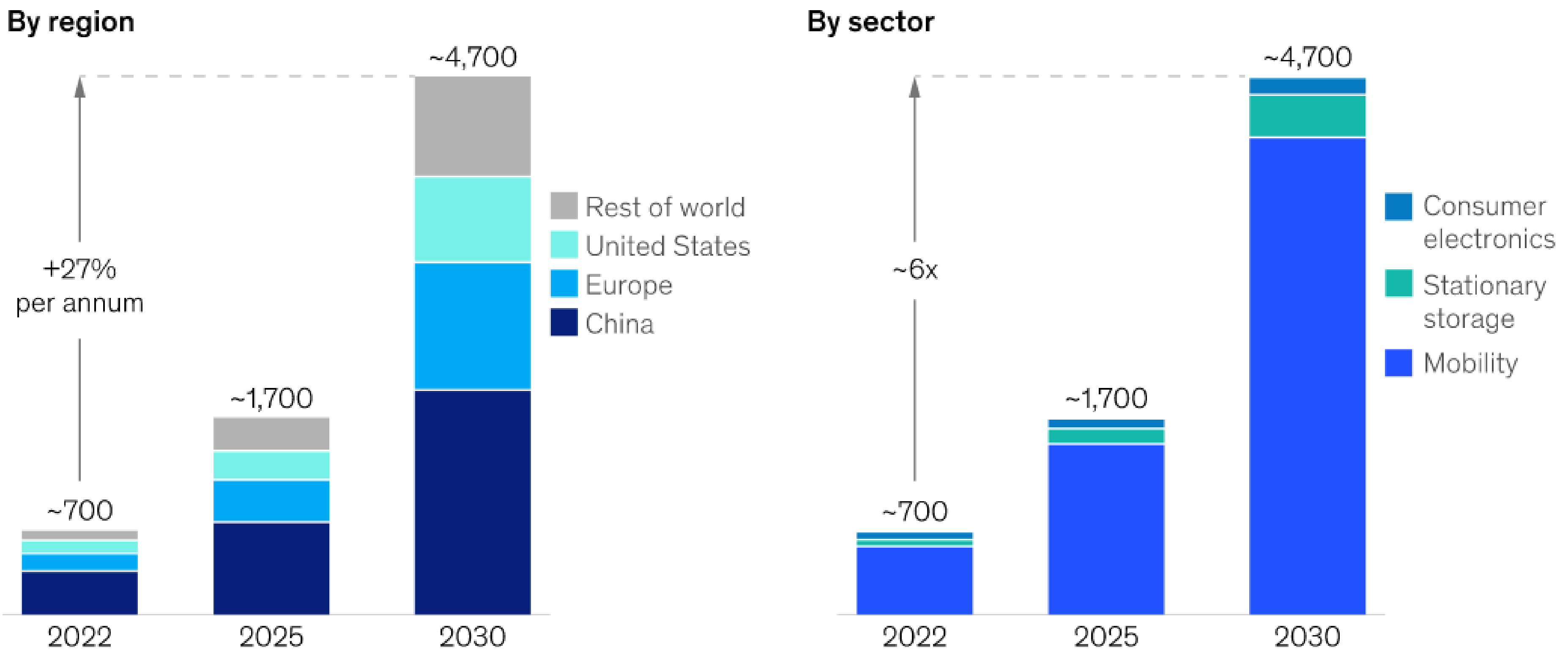


https://iopscience.iop.org/article/10.1088/0256-307X/40/4/048201/pdf

Market development by Mc Kinsey – Li-Ion Batteries

Li-ion battery demand is expected to grow by about 33 percent annually to reach around 4,700 GWh by 2030.

Global Li-ion battery cell demand, GWh, Base case



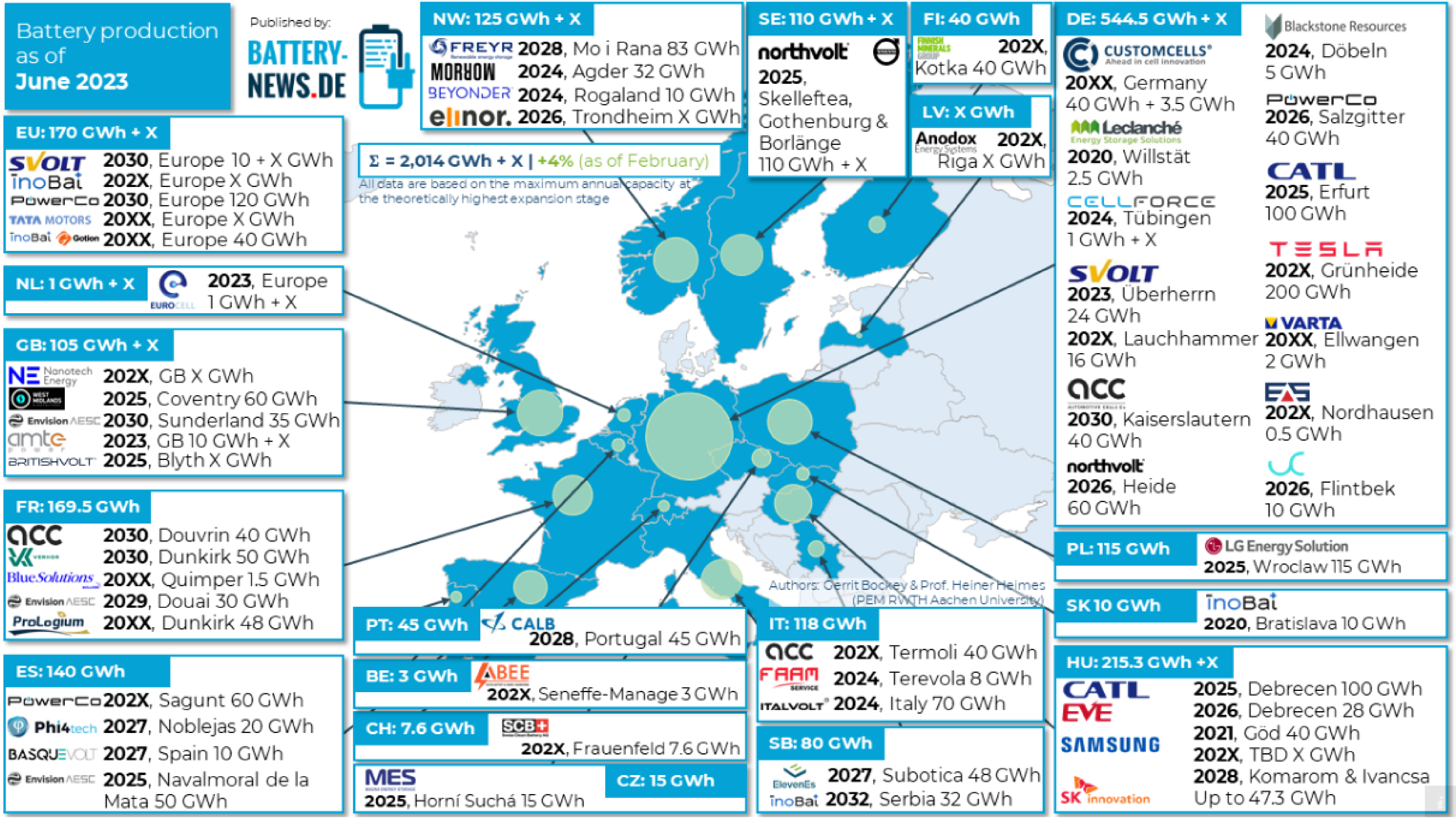
[1]Including passenger cars, commercial vehicles, two-to-three wheelers, off-highway vehicles, and aviation.
Source: McKinsey Battery Insights Demand Model

McKinsey & Company

https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular

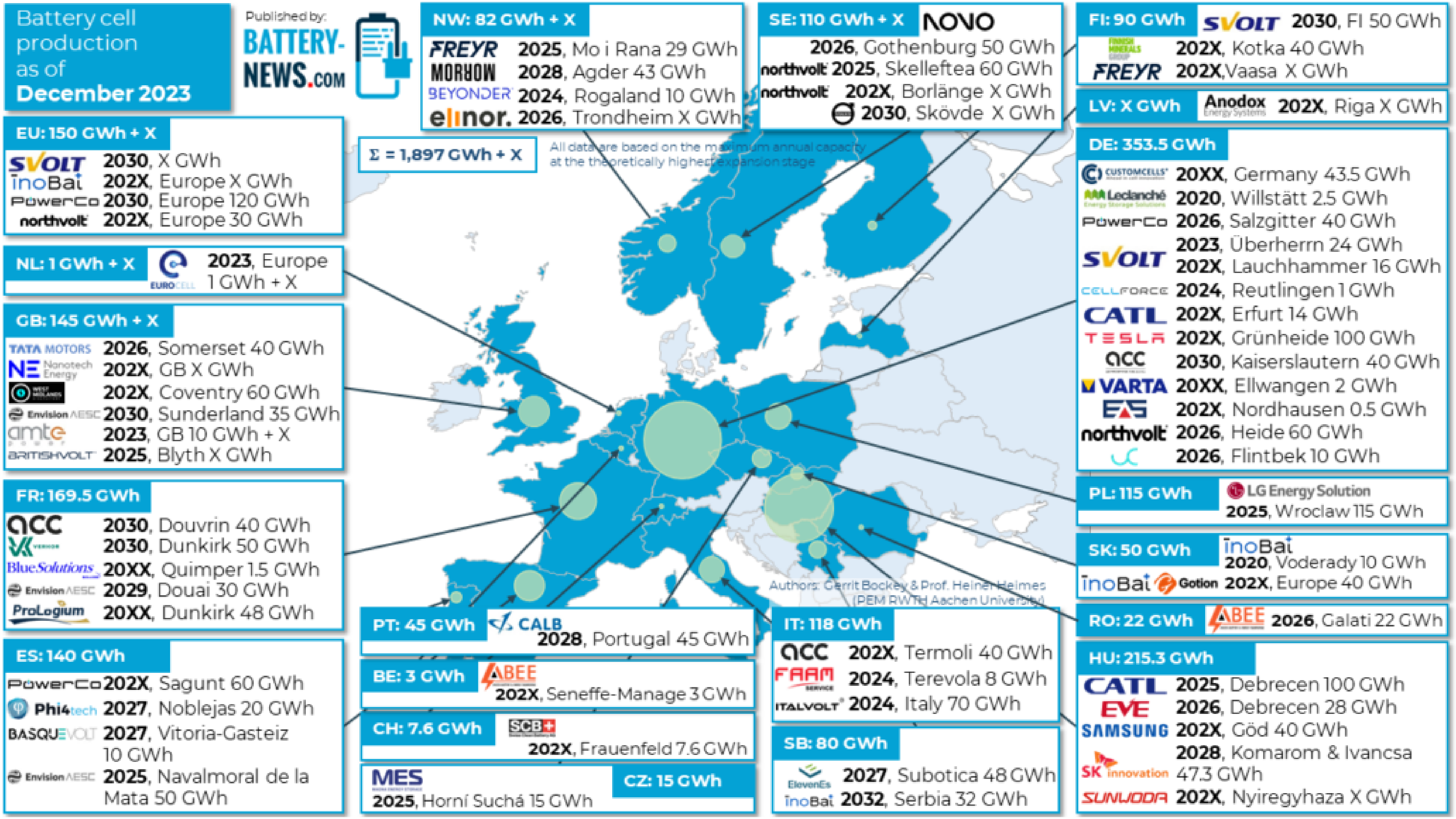
Battery Production Summary and Outlook

virtual vehicle



Cell Production Summary and Outlook

virtual vehicle



Battery Safety

Department: Electric, Electronics and Software, Group: Battery

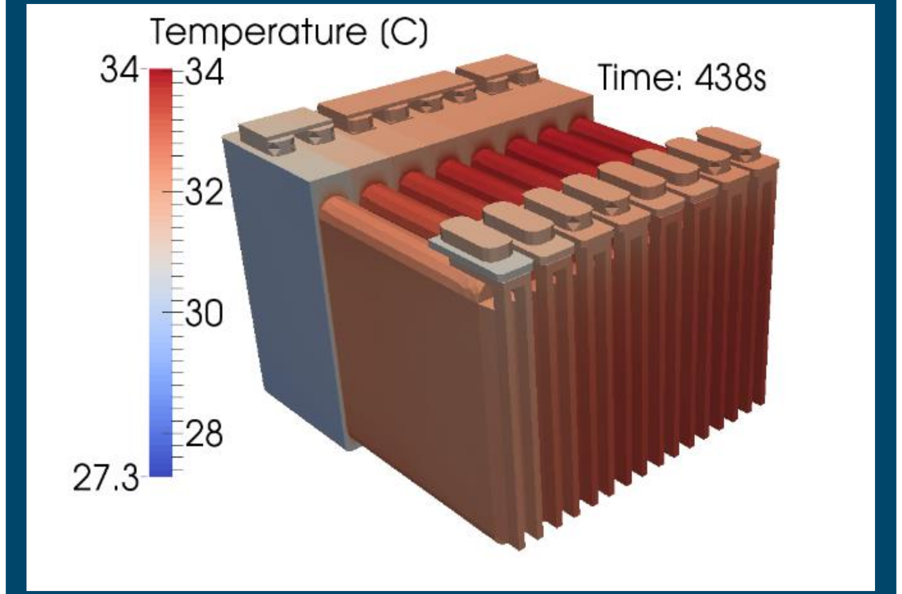
Thermal-Runaway Test Bench

- Test-rig-development for thermal-runaway (TR) characterization
- Detailed thermal analysis
- Vent-gas-analysis and modeling (rate/amount, toxicity)
- TR propagation tests
- Special thermal-management issues

Battery Test Bench

- Test setup (DoE) and battery testing
- Cycling capabilities on cell level
- Thermal and mechanical validation and verification
- Ageing or characterization tests
- Statistical modeling and prediction
- Life cycle

Battery Modeling and Simulation



- Electric, thermal and chemical simulation of batteries
- Microscopic, detailed cell modeling
  - From Particle to cell, porosity
- 3D (FE) simulation TR and TR propagation
- Parameter optimization

Source: Ars Technica 08/2016

Source: Forbes 03/2022

Source: Energyworld.com 08/2022

CAR FIRES BY VEHICLE TYPE

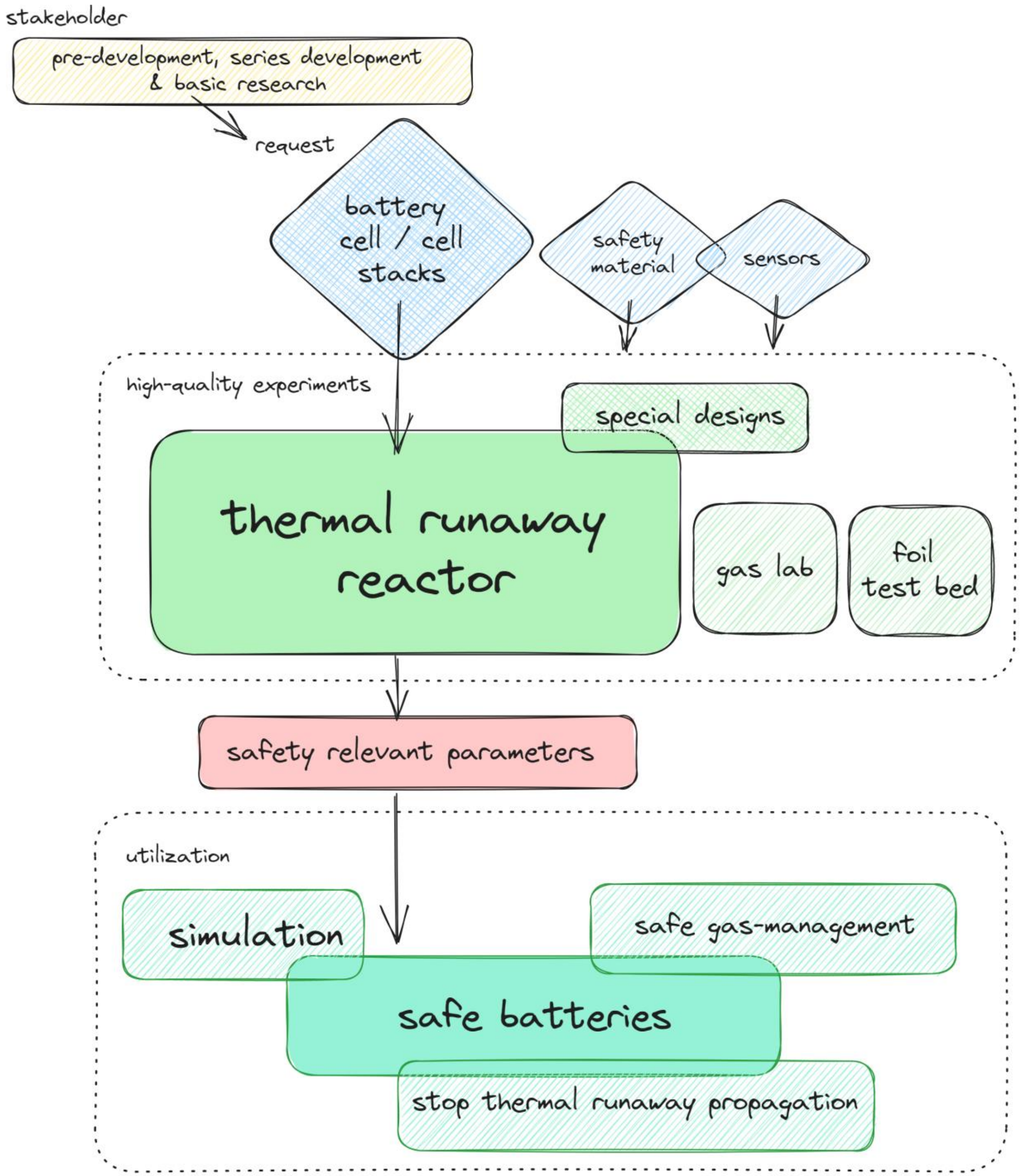
Rank and Fuel Type	Fires (per 100k Sales)	Total Fires
1 Hybrid	3,474.5	16,051
2 Gas	1,529.9	199,533
3 Electric	25.1	52

Source: Autoinsurance EZ 11/2022


8:00h
23:00h

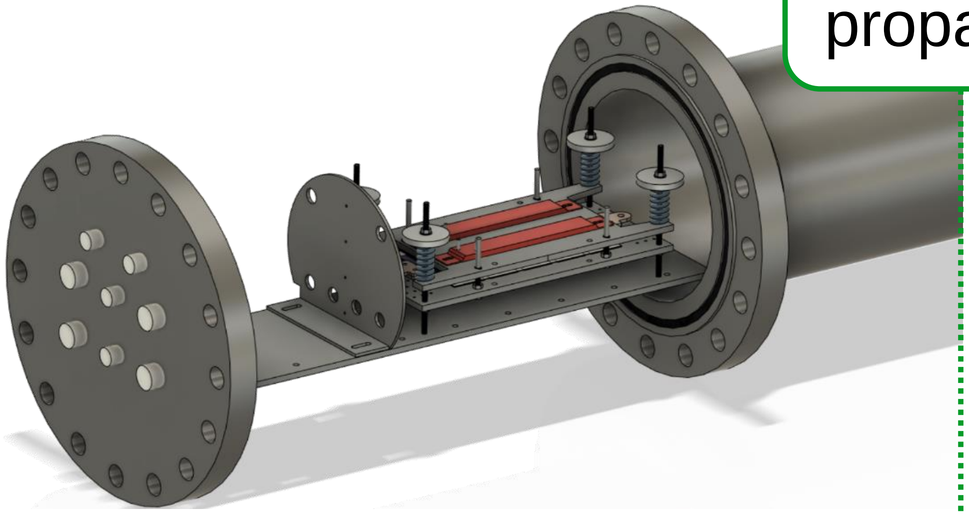
Battery safety @ Virtual Vehicle

- results provide the basis for safe batteries in pre-development, series development & basic research
- safety relevant parameters are used for simulation, the design for safe gas-management and to stop thermal-runaway propagation
- test battery cells, battery pack materials and sensors, which will be used in safe electric cars in the future
- special designs to address every customer need or research question
- continuity in follow-up projects and services



Thermal runaway experiments & analysis

Resp.:
A. Golubkov & C.Essl



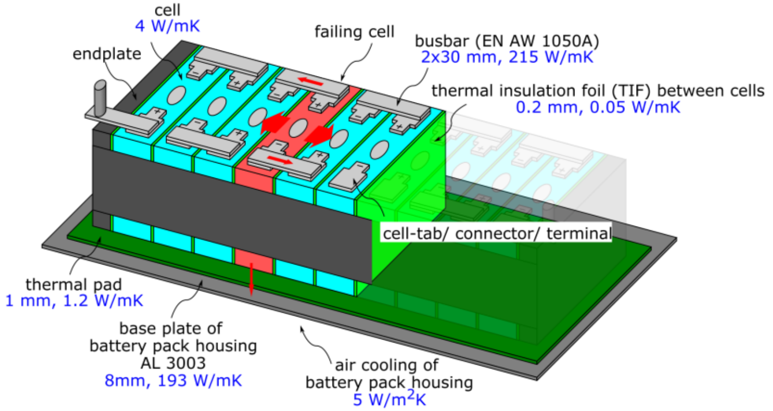
Input:
- All cell typs
- Single cells & cell stacks
- Immersioncooling
- Experiments in special thermal runaway test rigs

Results - Safety relevant parameters:
- Thermal behavior
- Vent-gas-rate/amount
- Gas composition
- Mechanical and electrical behavior

Relevant projects:
SafeBattery (FFG), SafeLIB (FFG), contract research

Thermal runaway propagation prevention

Resp.:
A. Golubkov

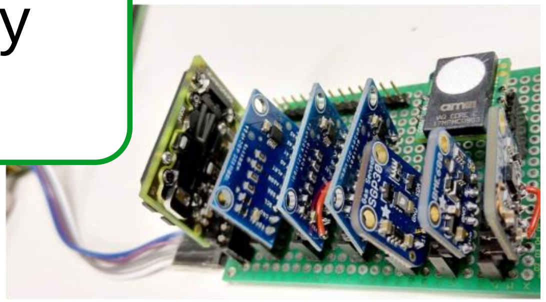


- Emergency cooling
- Thermal insulation between cells
- Prevention of electric arcs
- Particle analysis

Ref.:
Golubkov et.al. (2021): *A. W. Golubkov, "Safety of Li-ion Batteries for Electric Vehicles," Graz University of Technology, 2021, doi:* 10.3217/epzsr-94h43.
Essl et al. (2020): *Journal of The Electrochemical Society 2020; 167: 130542. DOI: 10.1149/1945-7111/abbe5a*

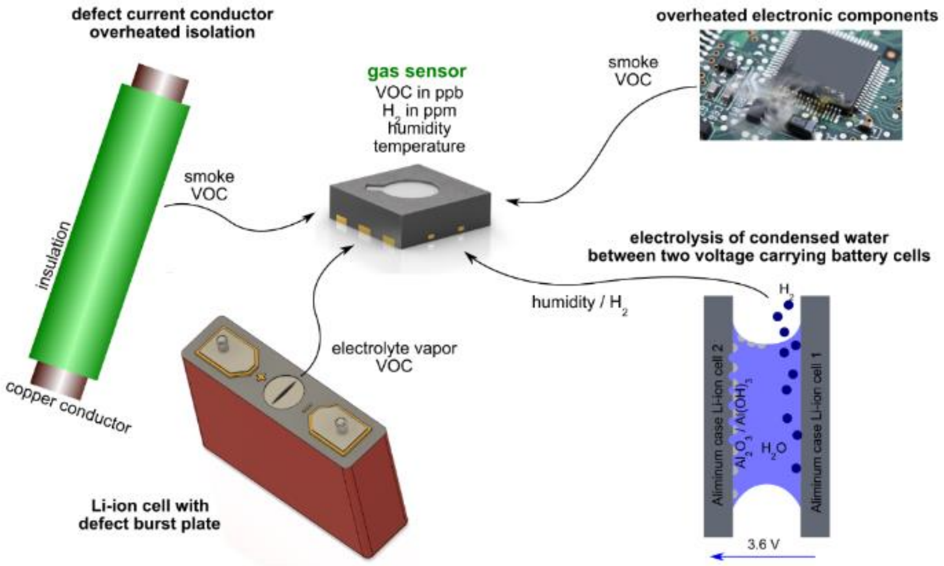
Projects and results (2/2)

Thermal runaway detection



Resp.:
C.Essl

- Gas sensors for early battery failure detection
- Comparison of different detection methods

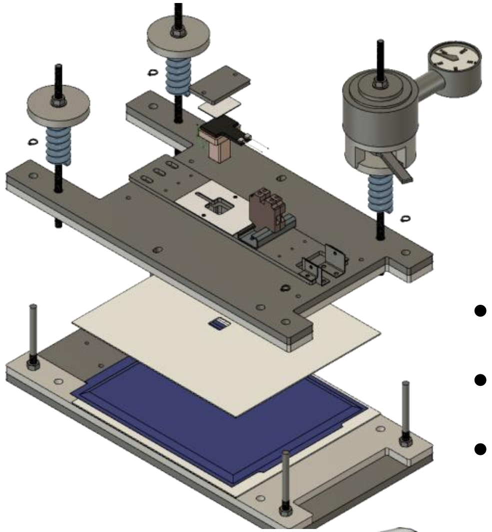


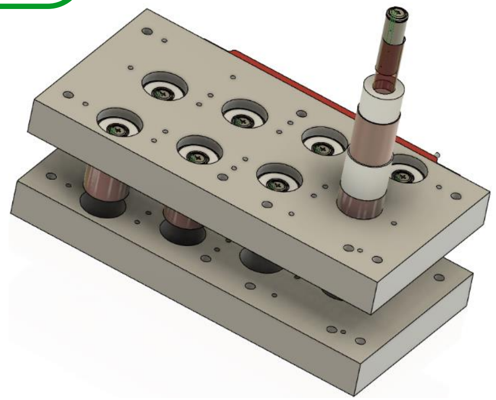
Relevant projects:
FFG GallON & FFG SafeION,

Ref.: Essl et al. (2021): *Batteries 2021; 7, 25, DOI: 10.3390/batteries7020025*

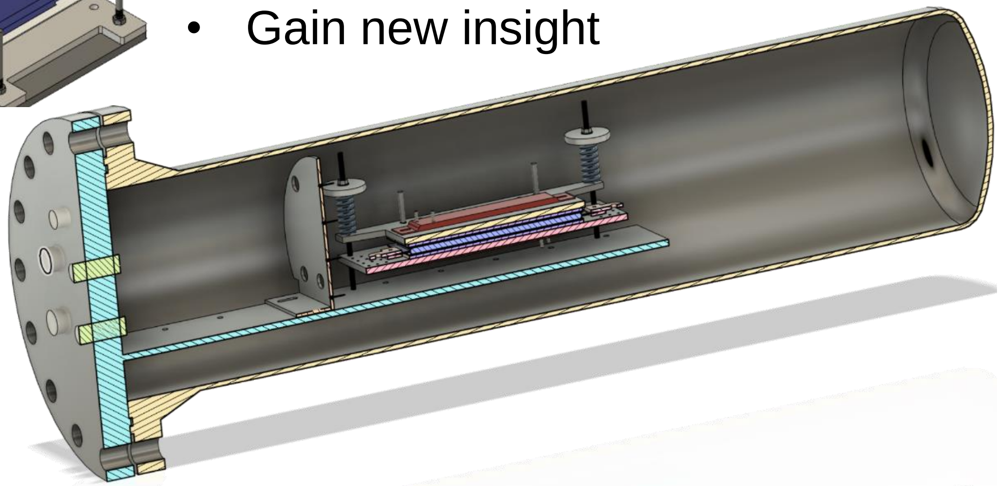
Thermal runaway special designs

Resp.:
A. Golubkov





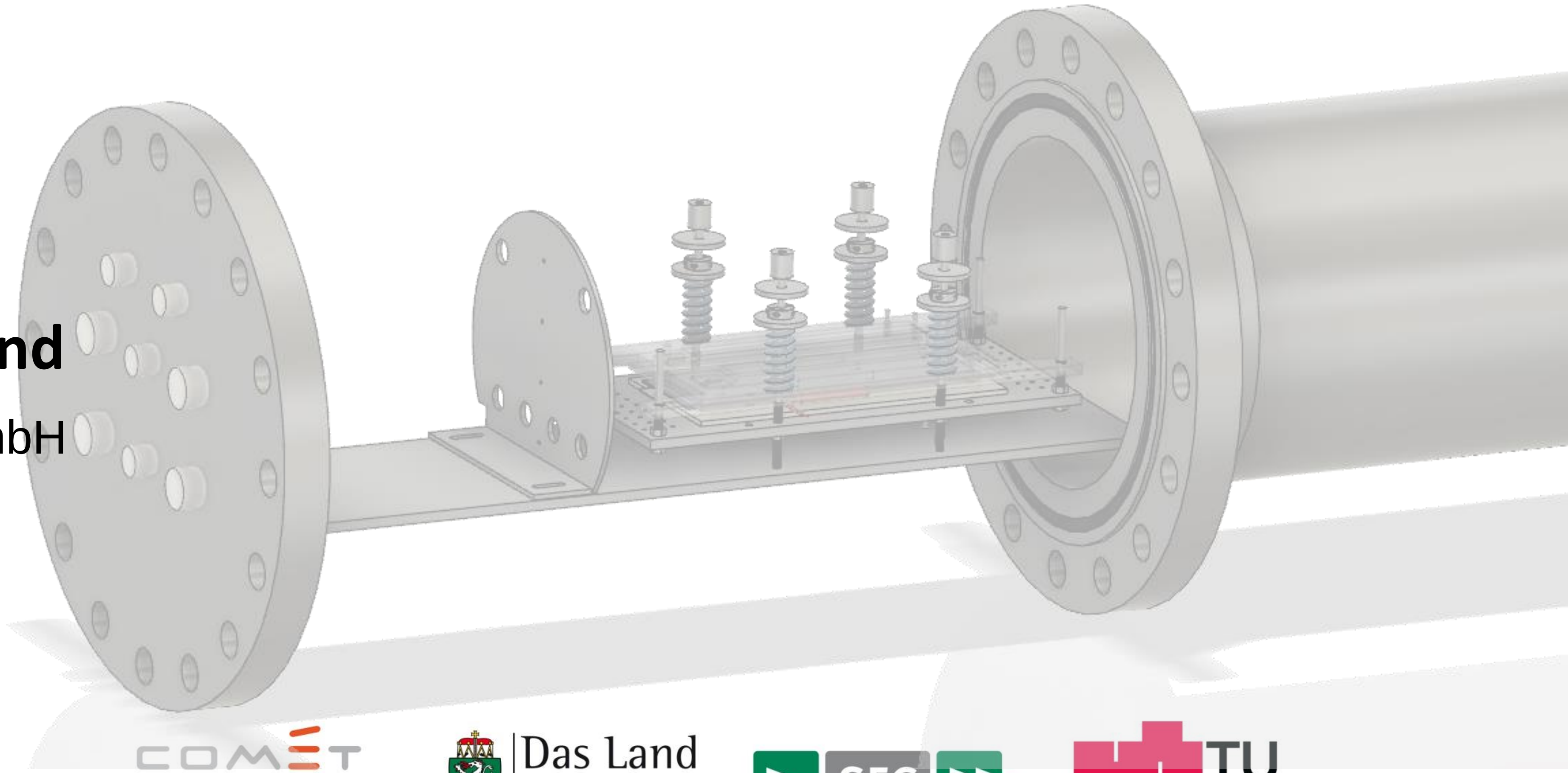
- Custom made for each cell type
- New trigger types
- Gain new insight



Ref.: A. W. Golubkov, "Safety of Li-ion Batteries for Electric Vehicles," Graz University of Technology, 2021. doi: 10.3217/epzsr-94h43.

virtual vehicle

BATTLAB THERMAL RUNAWAY TEST BENCH



Battery Misuse Test-stand

VIRTUAL VEHICLE Research GmbH

bmvit Bundesministerium für Verkehr, Innovation und Technologie | bmwfw Bundesministerium für Wissenschaft, Forschung und Wirtschaft | FFG | COMET Competence Centers for Excellent Technologies | Das Land Steiermark | SFG | TU Graz Graz University of Technology

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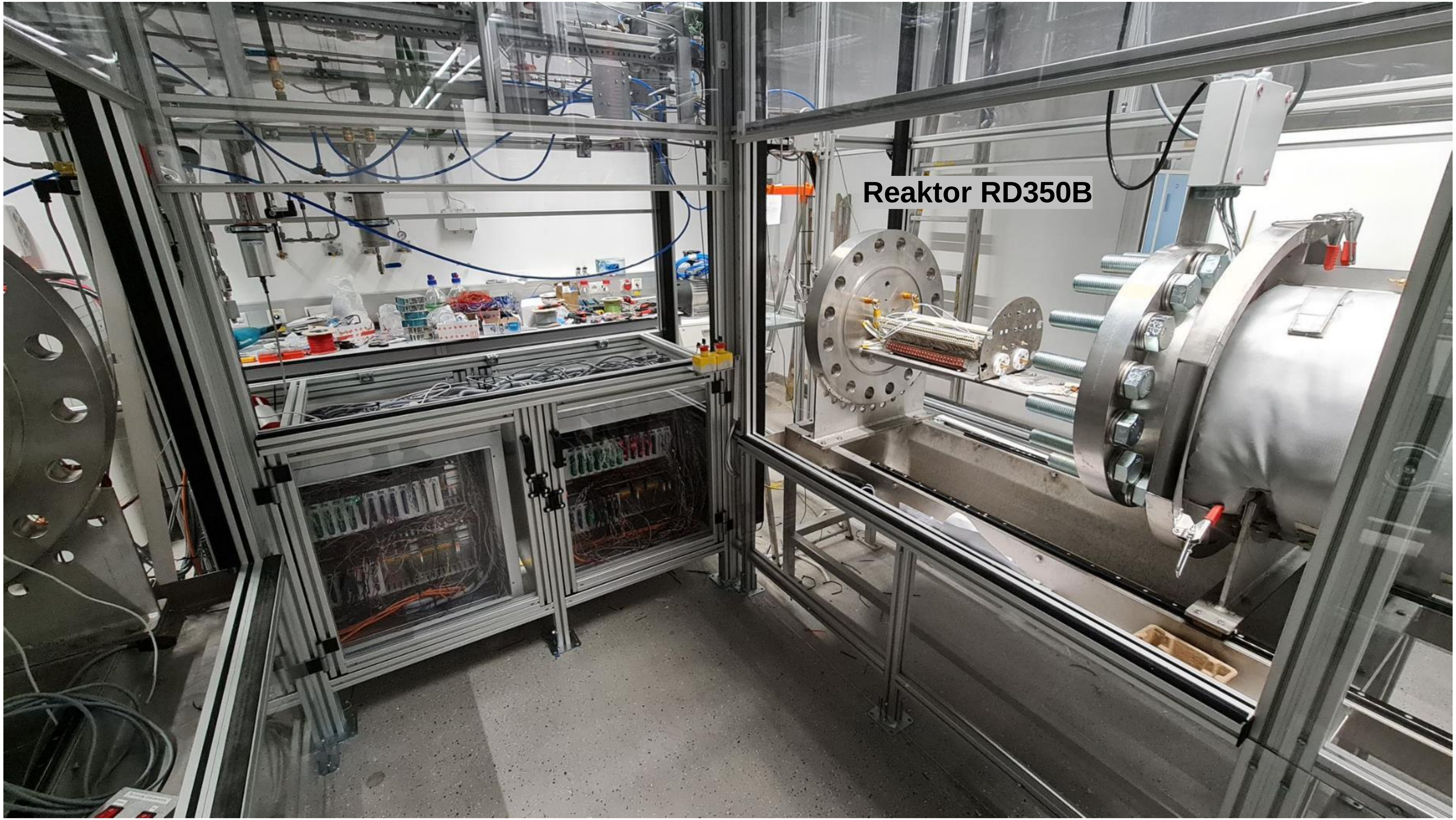
Thermal runaway test stand

BATTLAB THERMAL RUNAWAY TEST BENCH

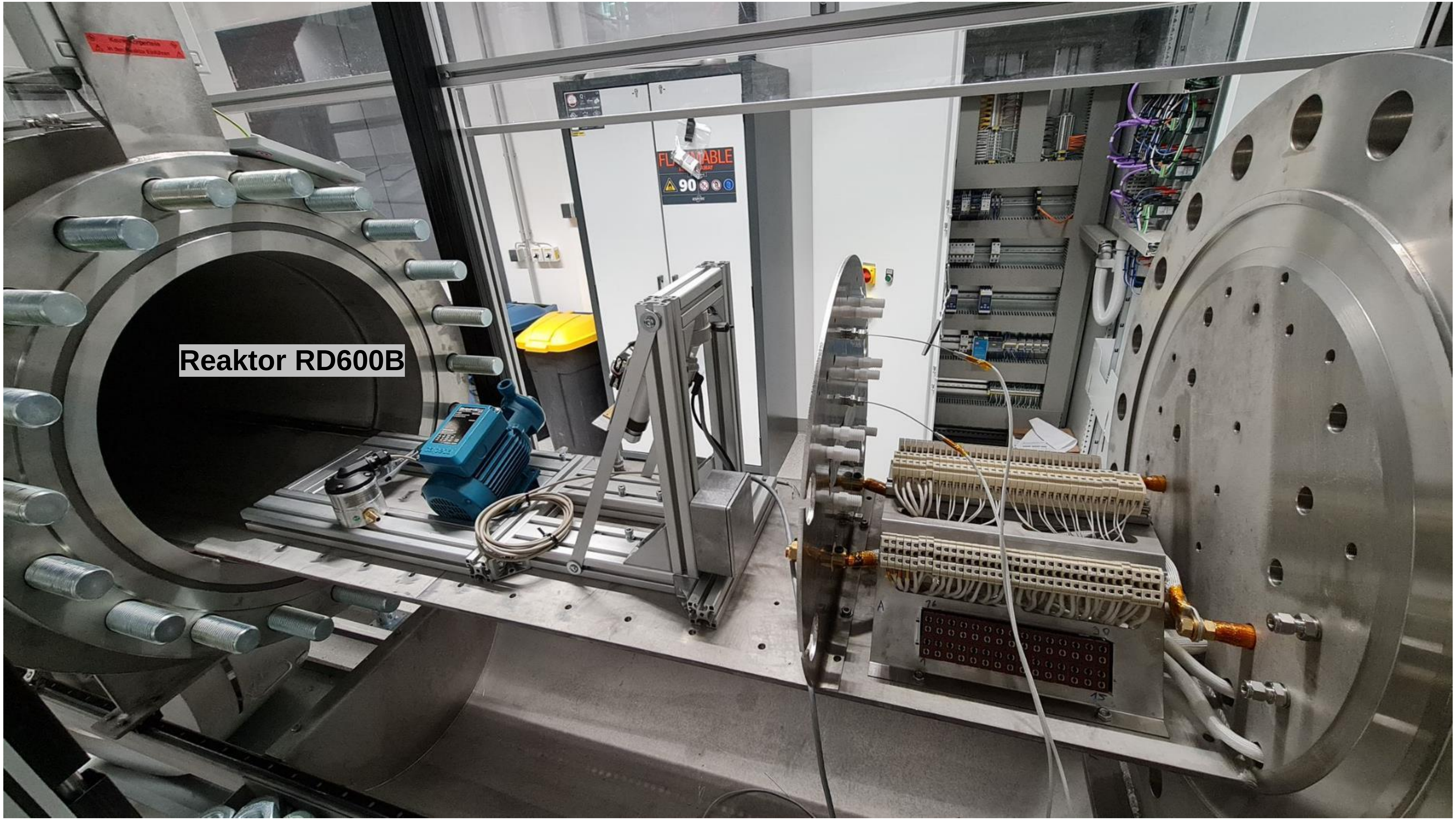
360° Webtour
https://www.v2c2.at/webtour360/batlab/

Thermal runaway test stand

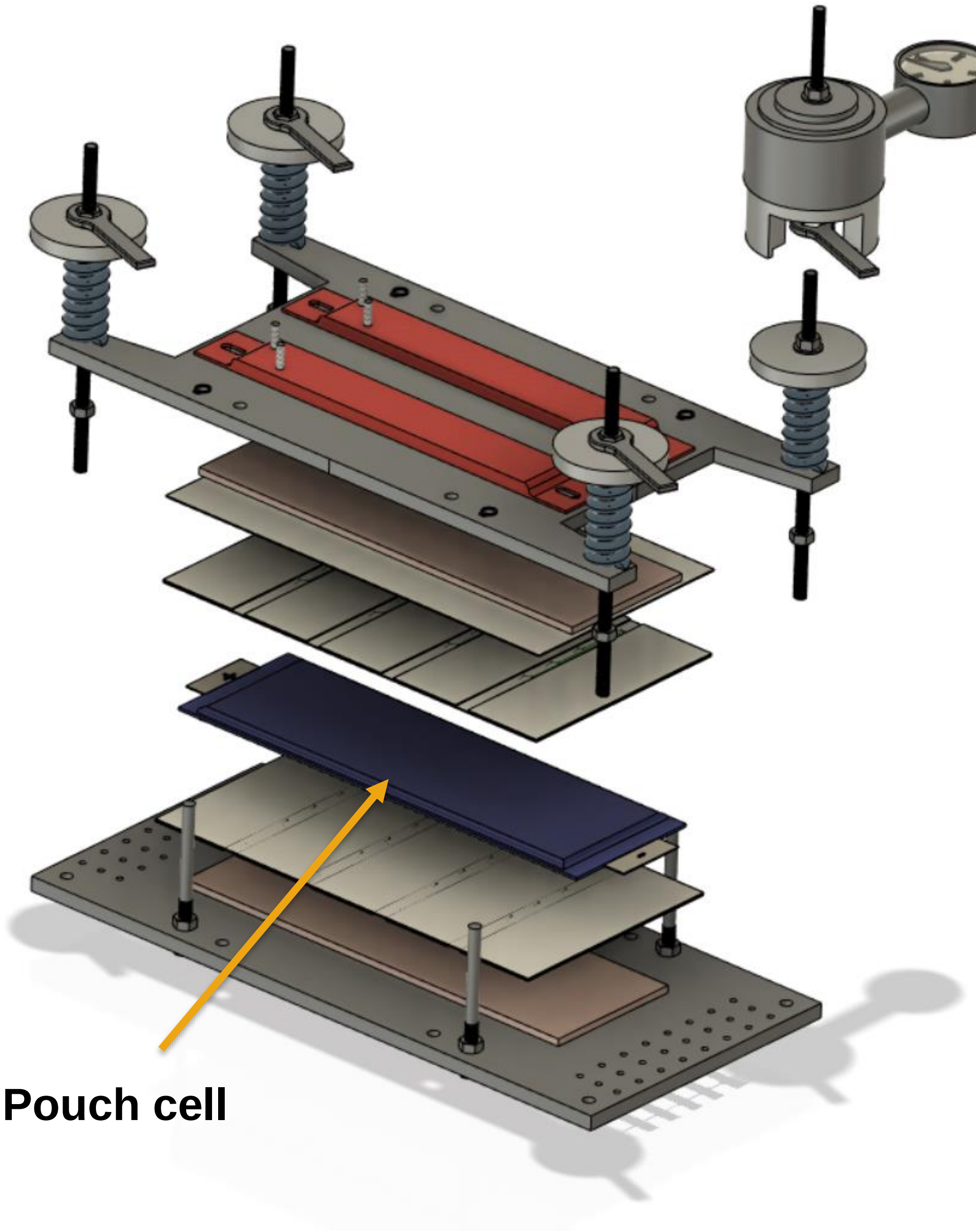
Thermal runaway test stand

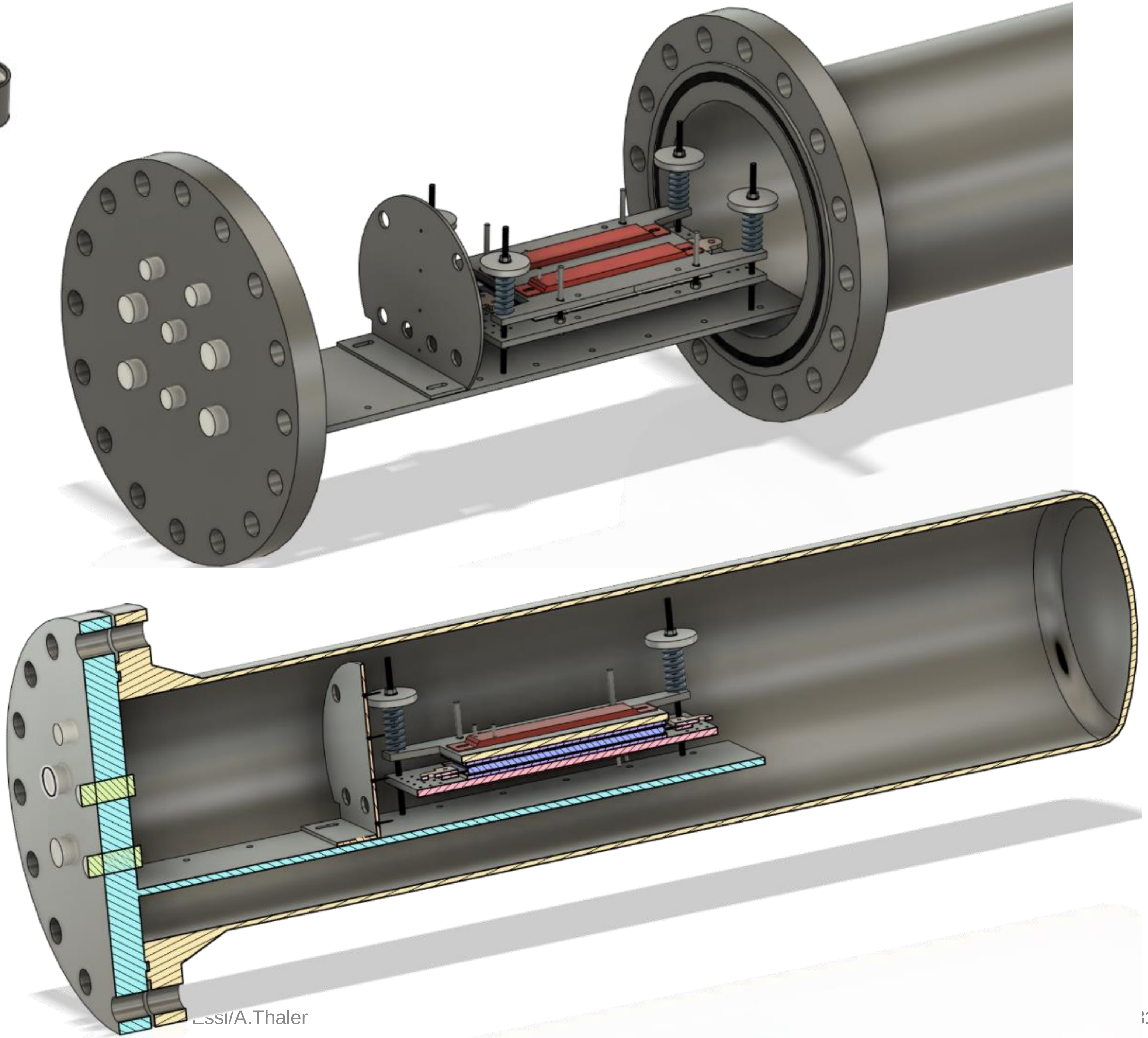


Thermal runaway test stand



Test setup reactor





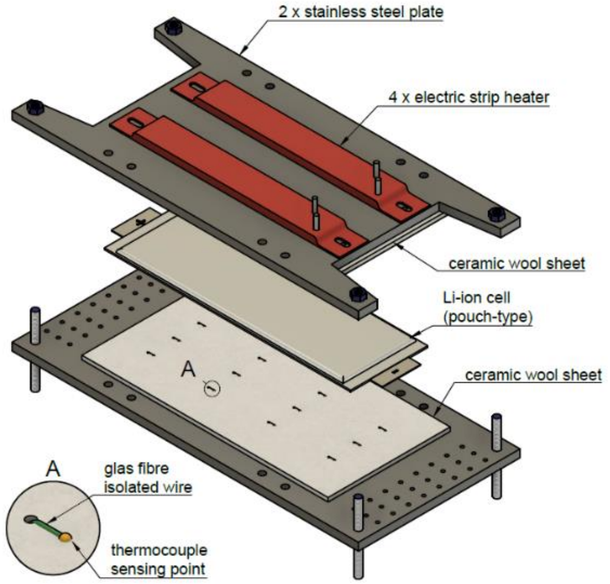
Thermal runaway trigger

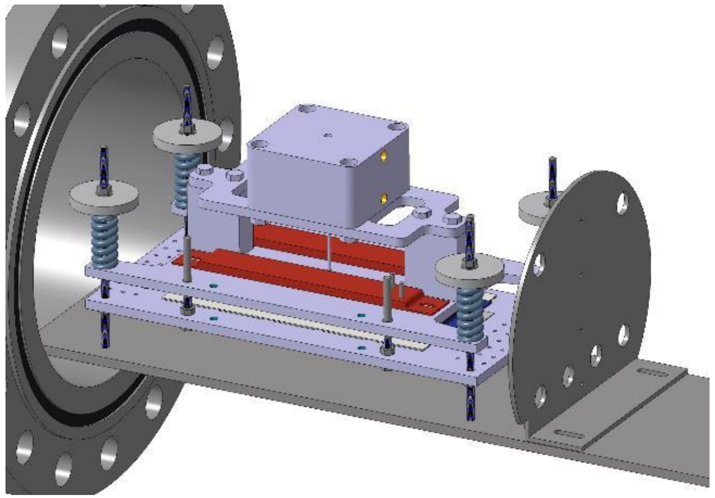
Trigger Types

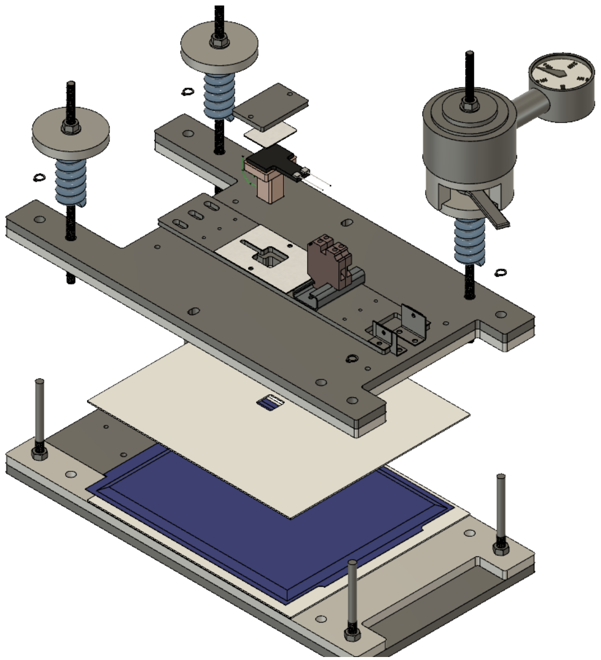
- Overtemperature
  - Both sides
  - One side
  - Full surface or hot spot
  - Different heating rates
- Nail-penetration
  - Different nail properties
  - Different nail velocity
  - Different penetration depth
- Overcharge
- External short circuit

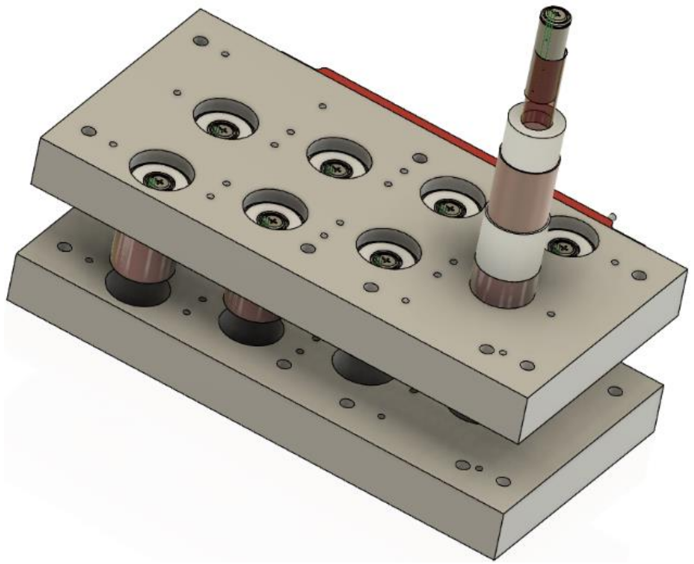
- Continuous improvements

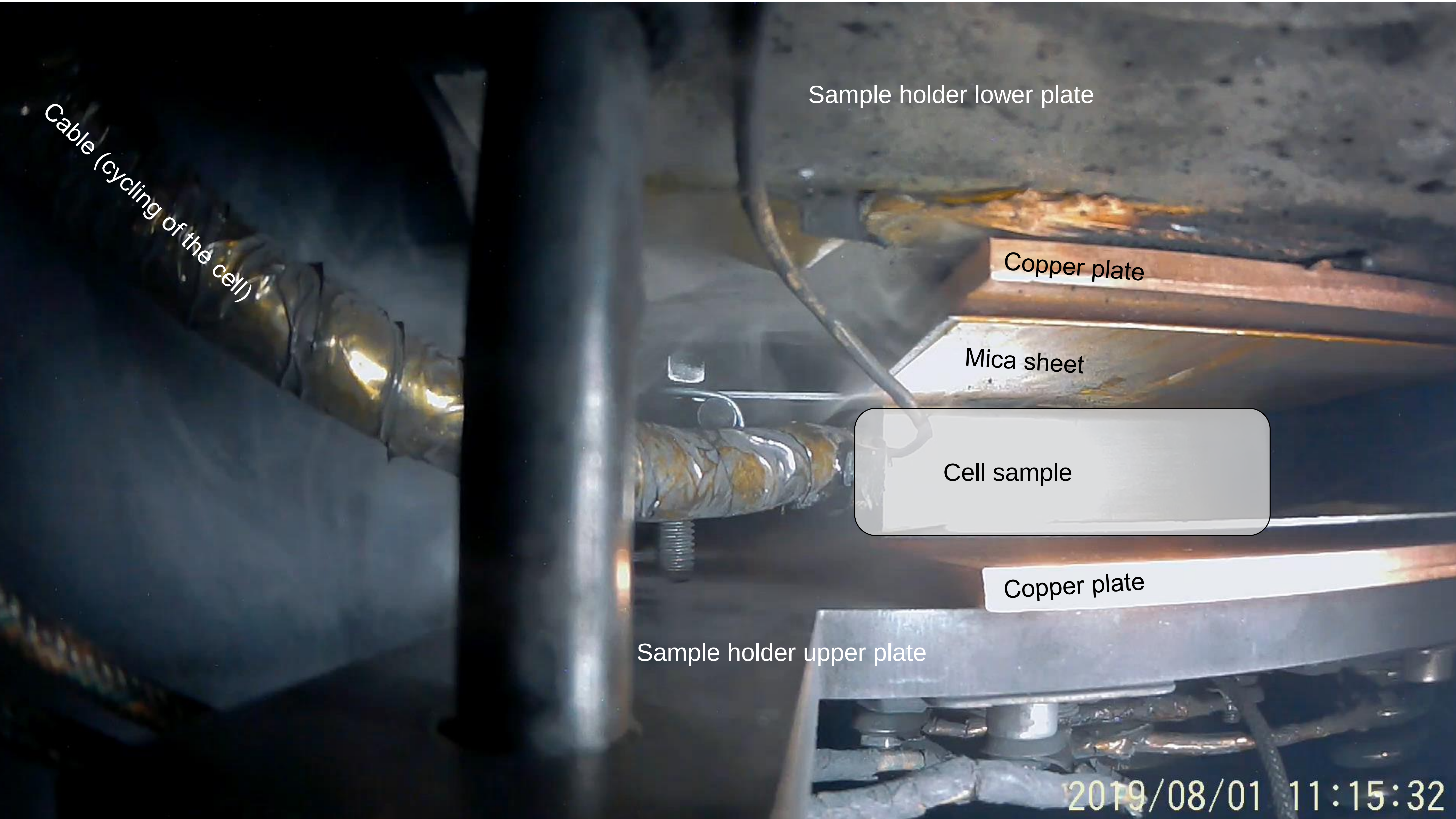
Examples:





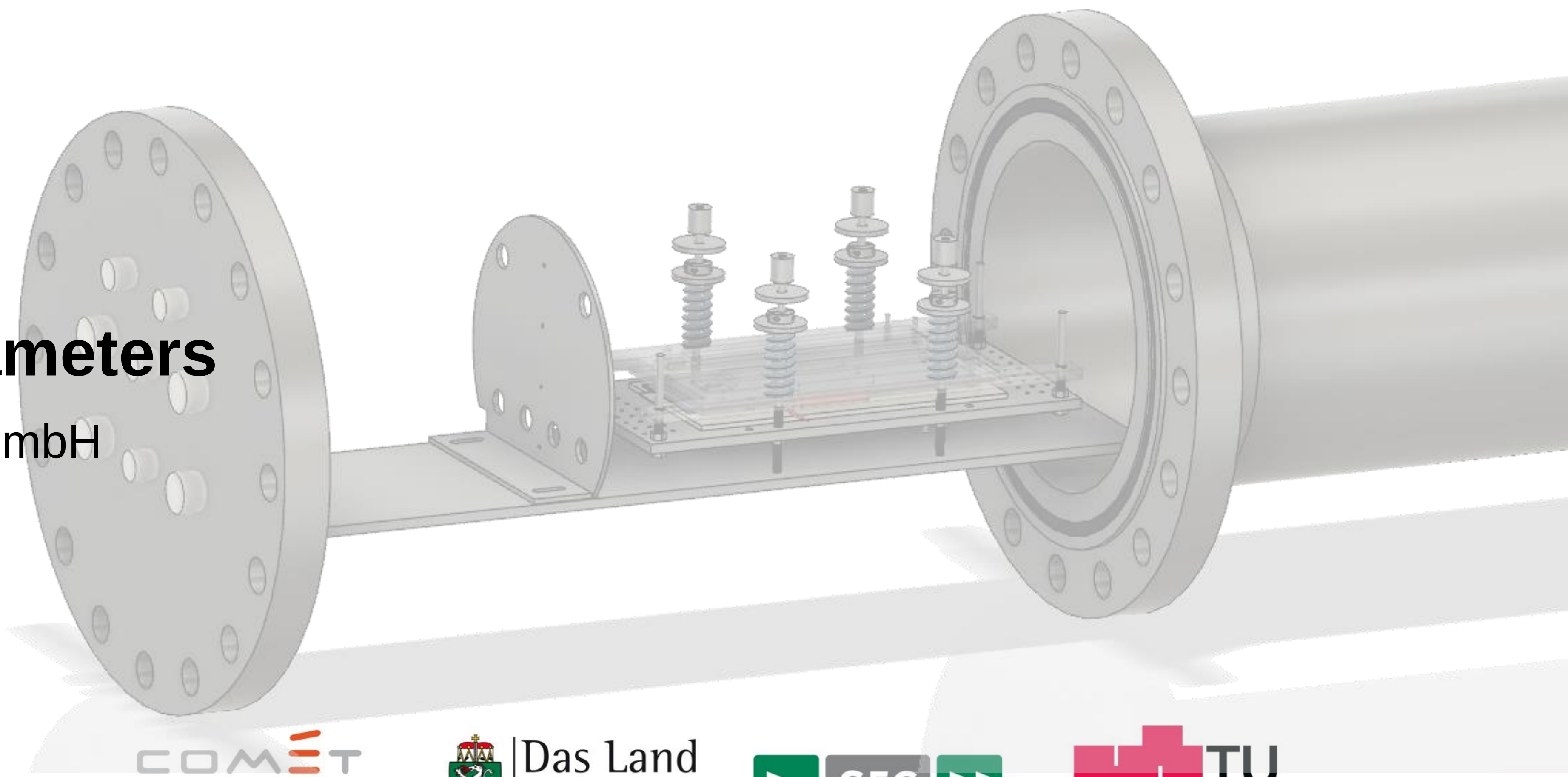





Sample holder lower plate
Cable (cycling of the cell)
Copper plate
Mica sheet
Cell sample
Copper plate
Sample holder upper plate
2019/08/01 11:15:32

Safety Relevant Parameters

VIRTUAL VEHICLE Research GmbH



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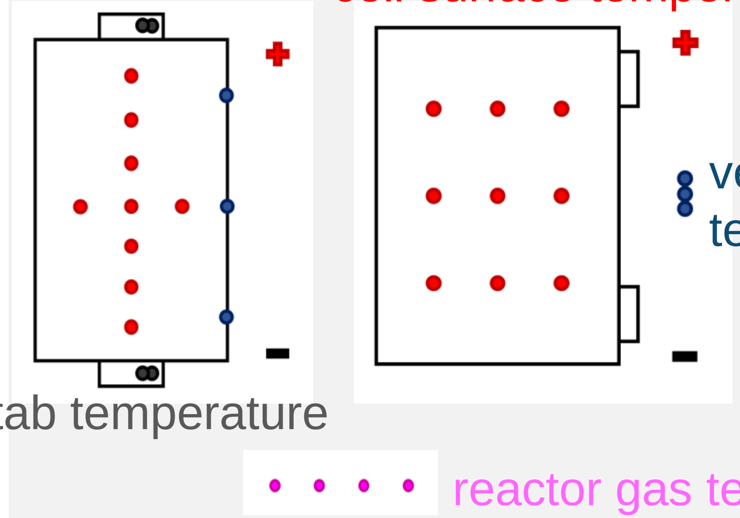
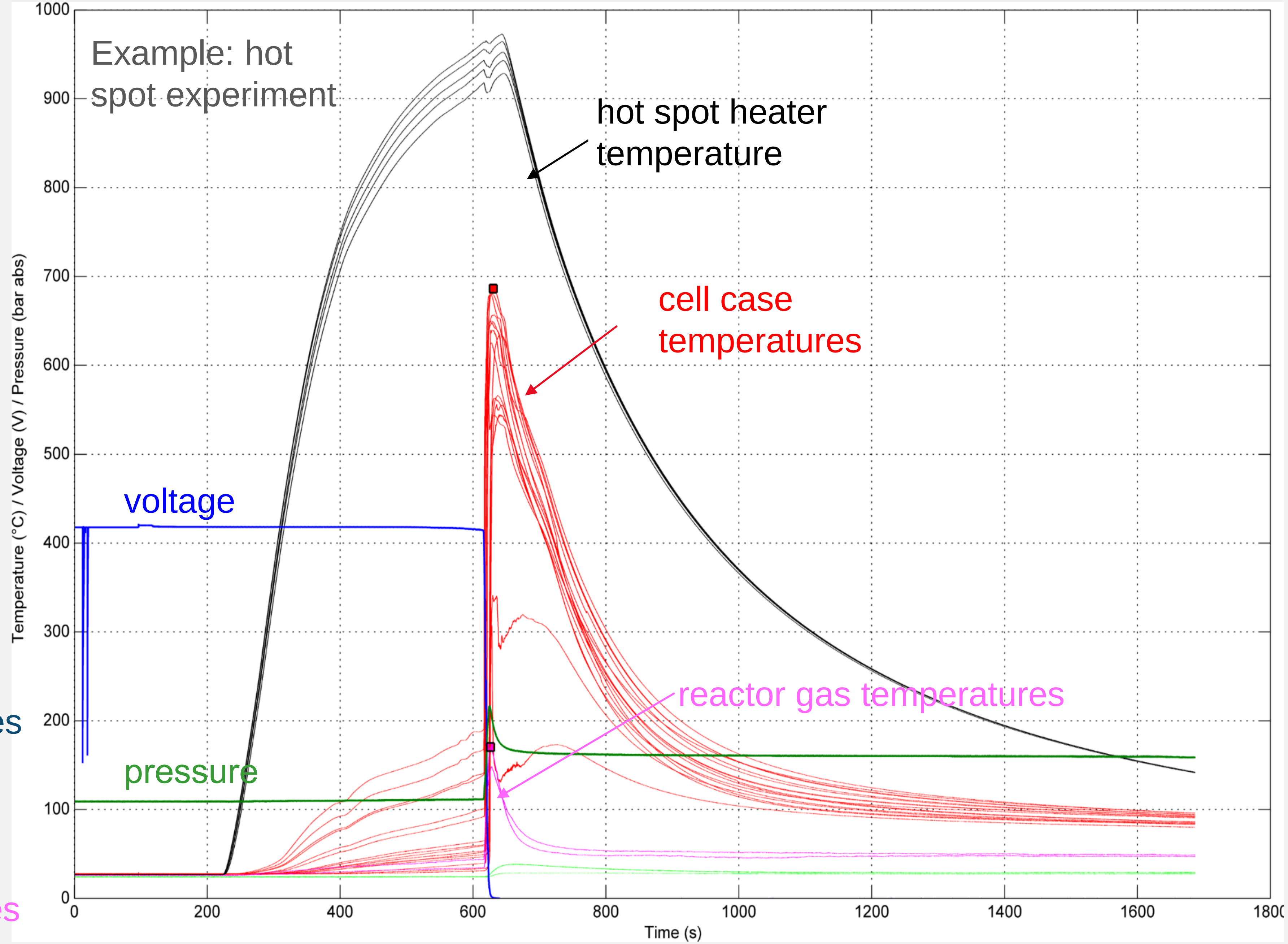
Thermal runaway test stand- Parameters

- Temperature information of
  - Cell surface
  - Vent gas
  - Reactor-gas

positions can be chosen

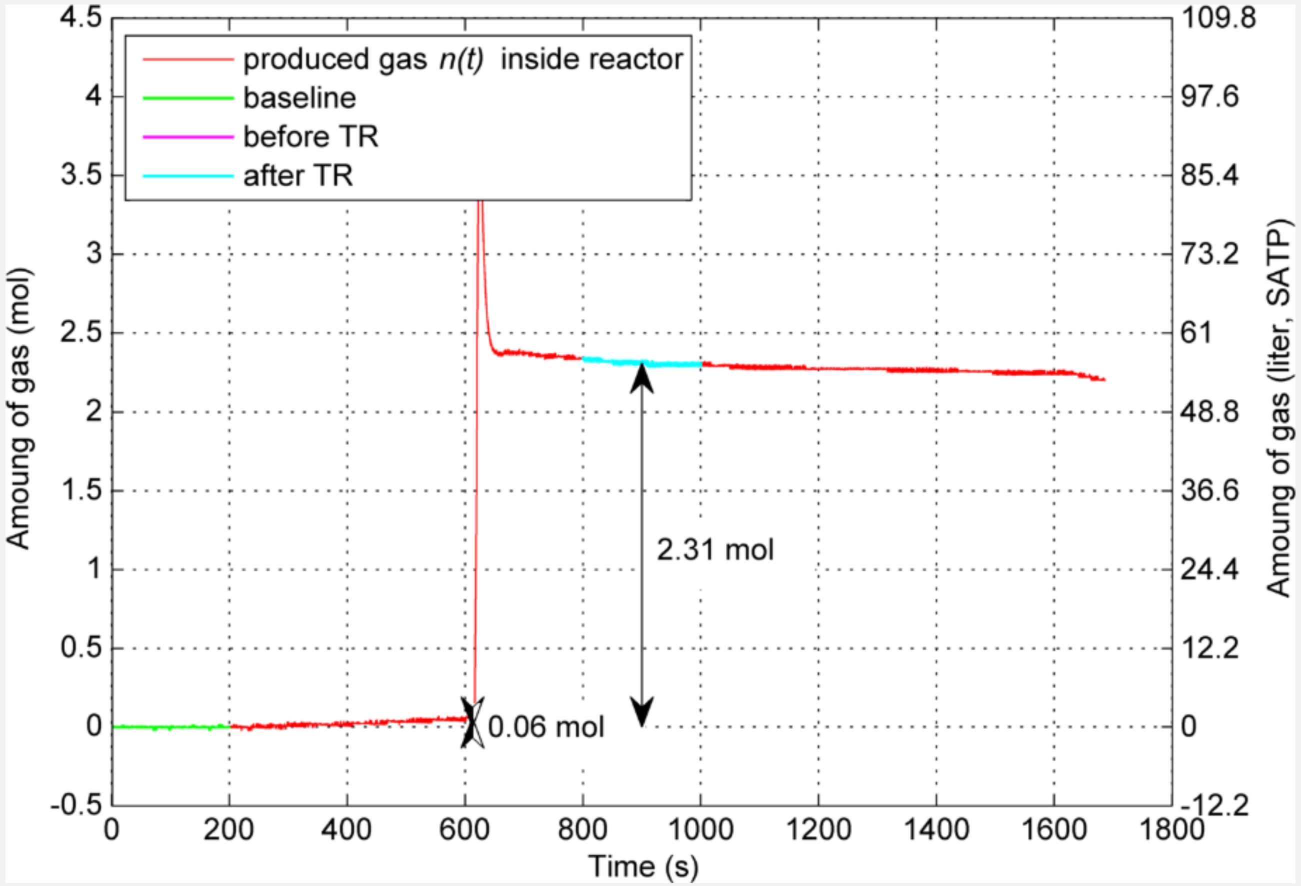
example positions:

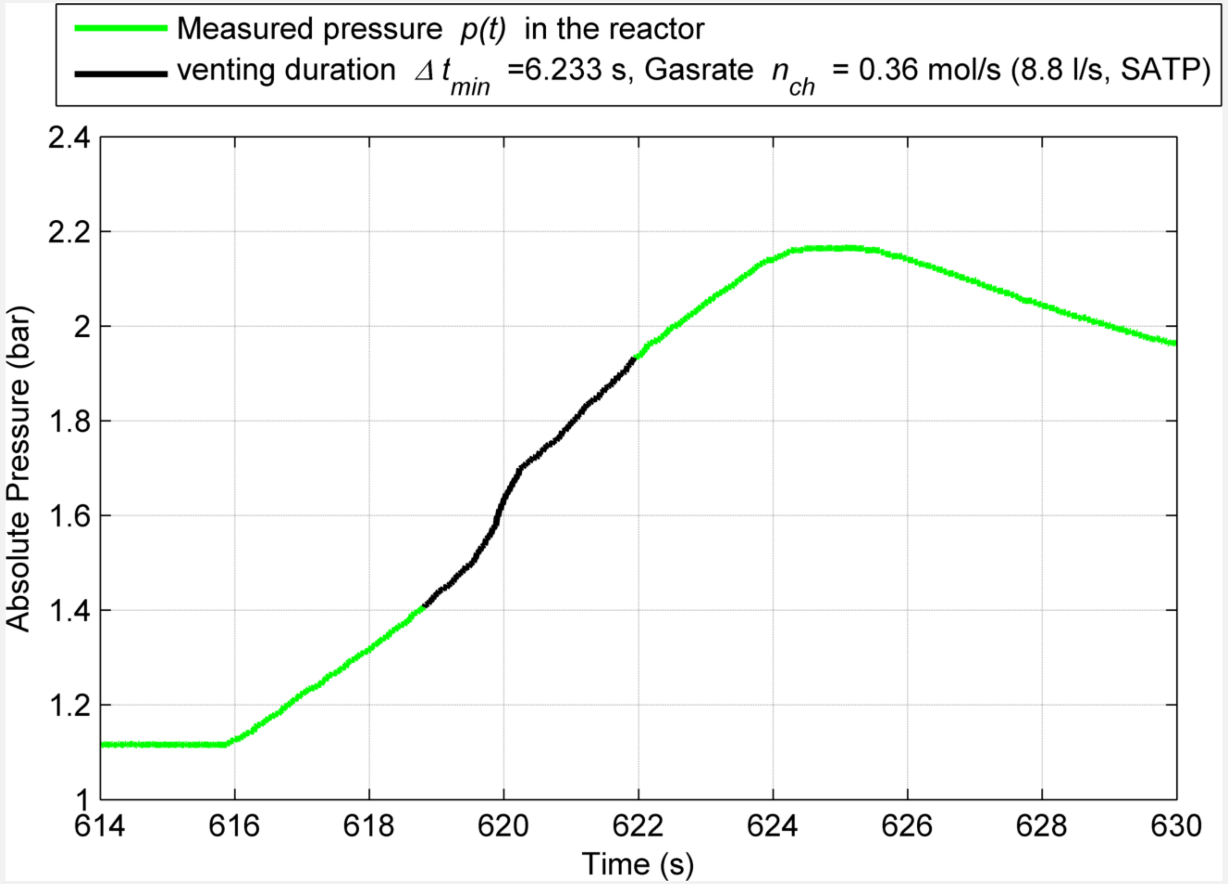




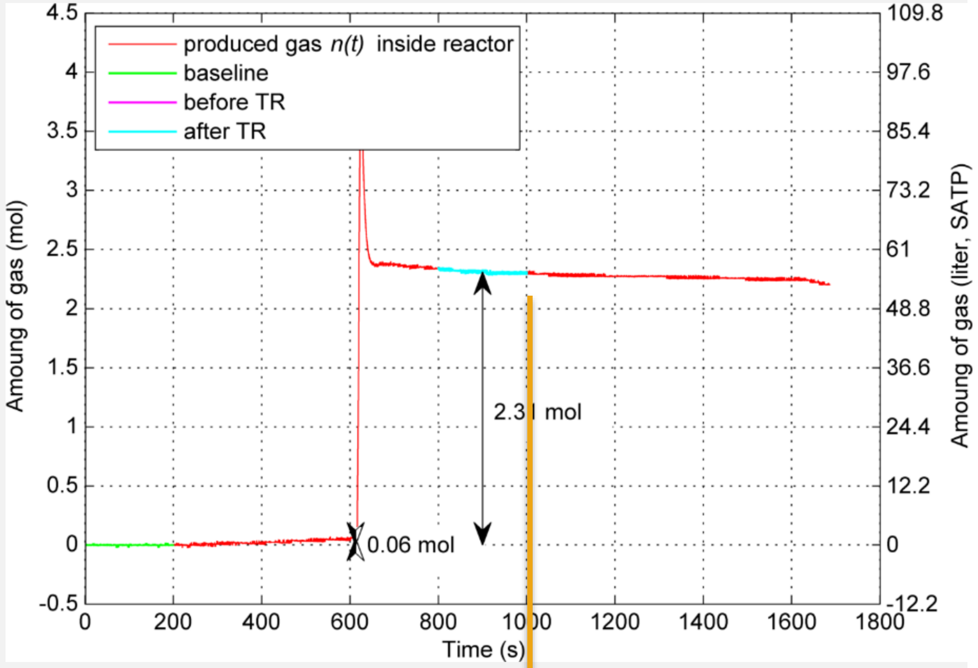
Measure pressure and temperature inside the reactor.
Get information about

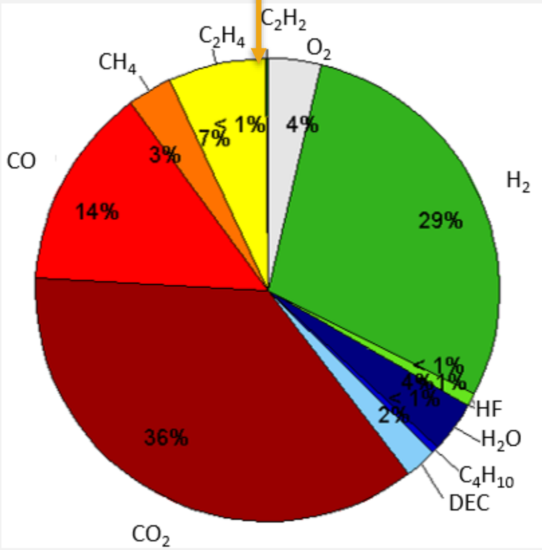
- Amount of produced gas
- Duration of the venting event
- Vent gas emission rate (speed of gas release)





Quantification and qualification of produced gas

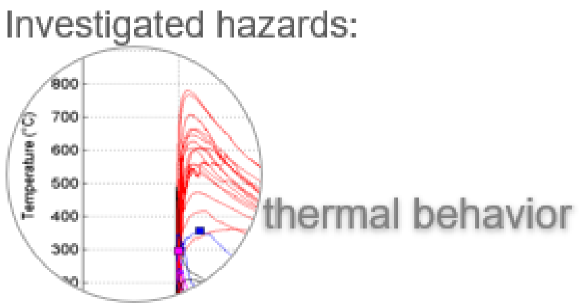


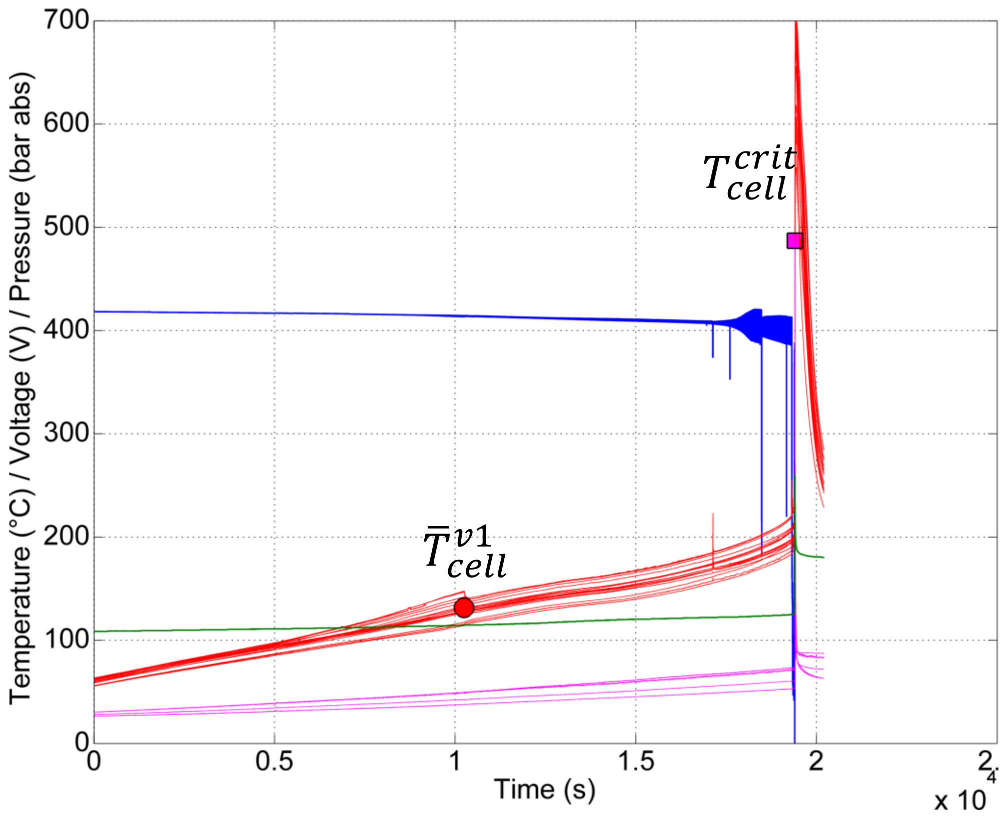


Inficon µGC Fusion
- H_2 (!)
- CO_2, CO, CH_4, hydrocarbons
- N_2, O_2
- Electrolyte

FTIR: Brucker MATRIX MG1
- Electrolyte vapor
- H_2O, CO_2, CO, CH_4, hydrocarbons
- HF

Safety relevant parameters – Cell Temperature

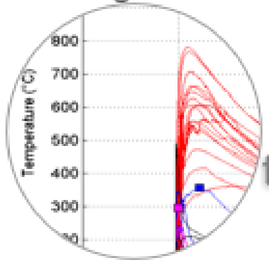


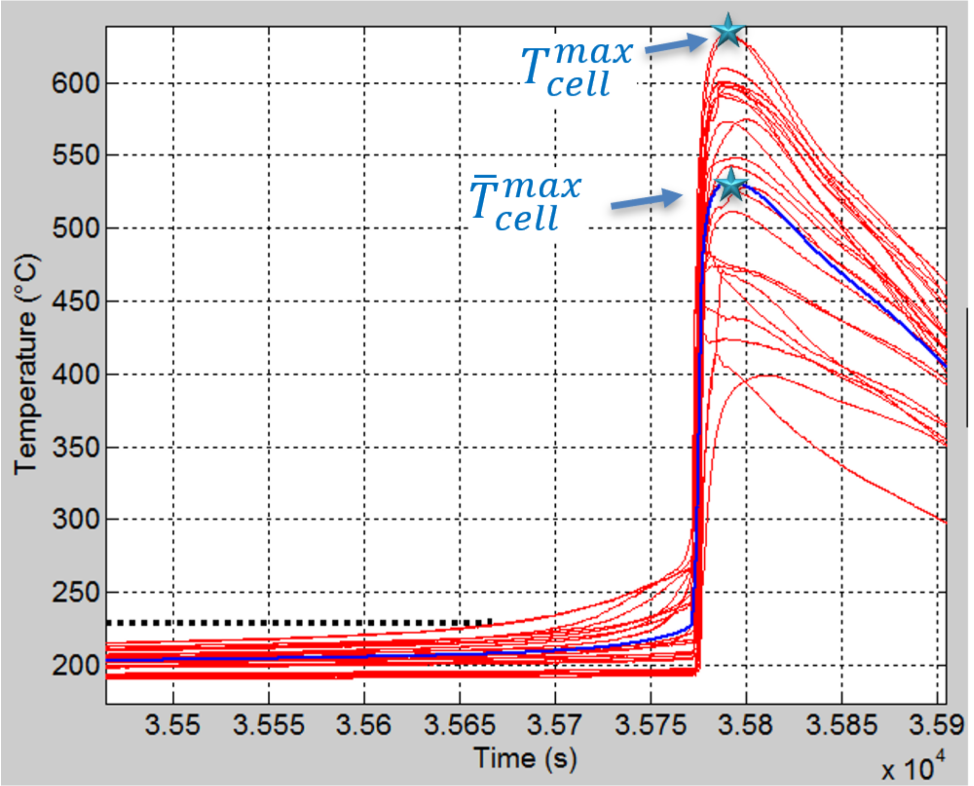


- $\bar{T}_{cell}^{v1}$ (°C) the average measured temperature of all thermocouples on the cell surface when the first venting starts
- T_{cell}^{crit} (°C) the temperature of the one cell-surface thermocouple, which is the first to exceed the temperature rate of 10°C/min
- $\bar{T}_{cell}^{v2}$ (°C) the average measured temperature of all thermocouples on the cell surface when the second venting starts

Safety relevant parameters – Cell Temperature

Investigated hazards:

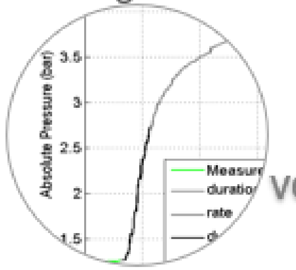




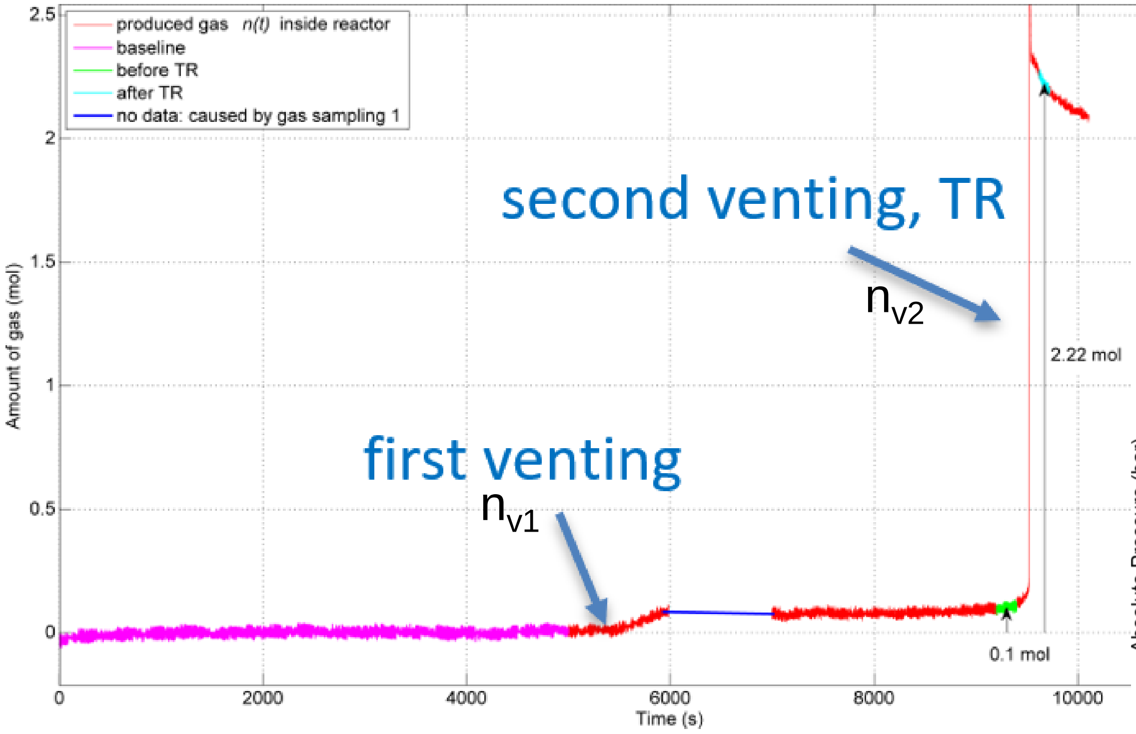
- T_{cell}^{max} (°C) the maximum recorded temperature of one of the thermocouples on the cell surface
- $\bar{T}_{cell}^{max}$ (°C) the maximum average surface temperature of all thermocouples on the cell surface
- T_{vent}^{max} (°C) the maximum recorded temperature of one of the thermocouples at the venting positions; this parameter is only rarely measured at pouch cells without defined venting, such as the investigated cell

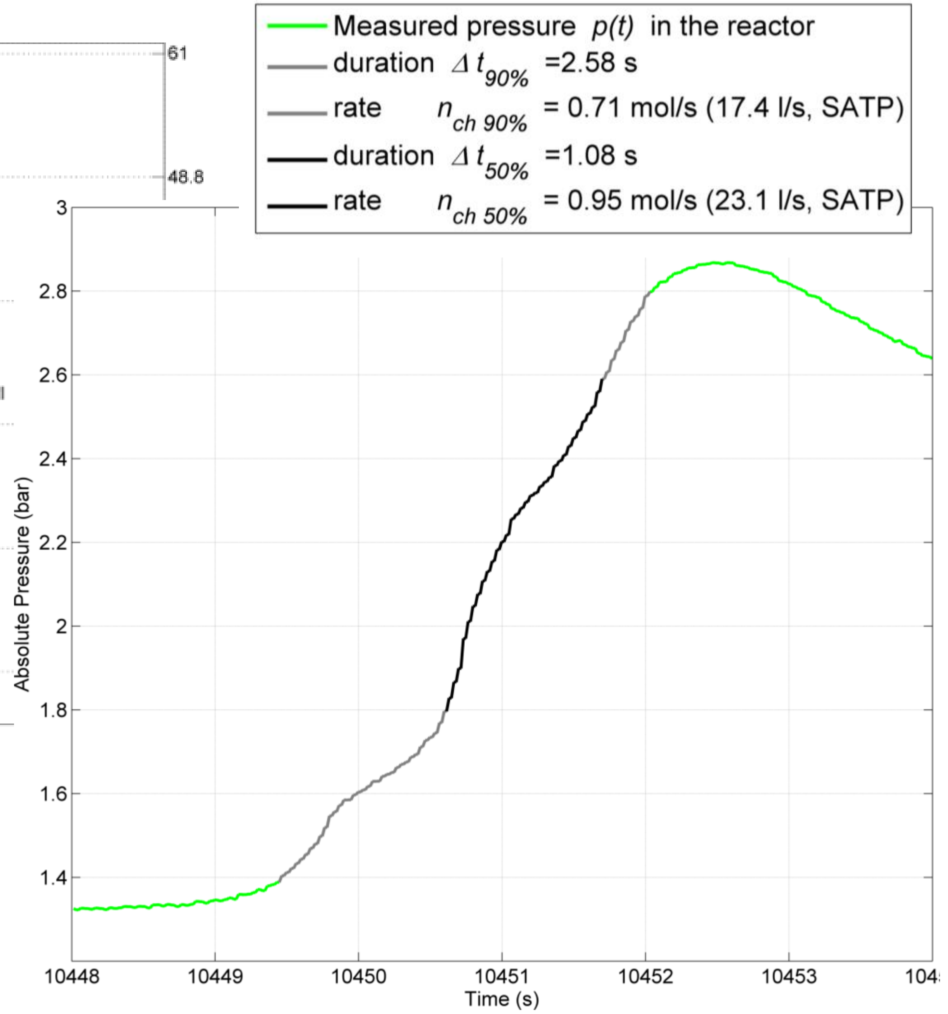
Safety relevant parameters – Released Gas

Investigated hazards:



vent gas emission





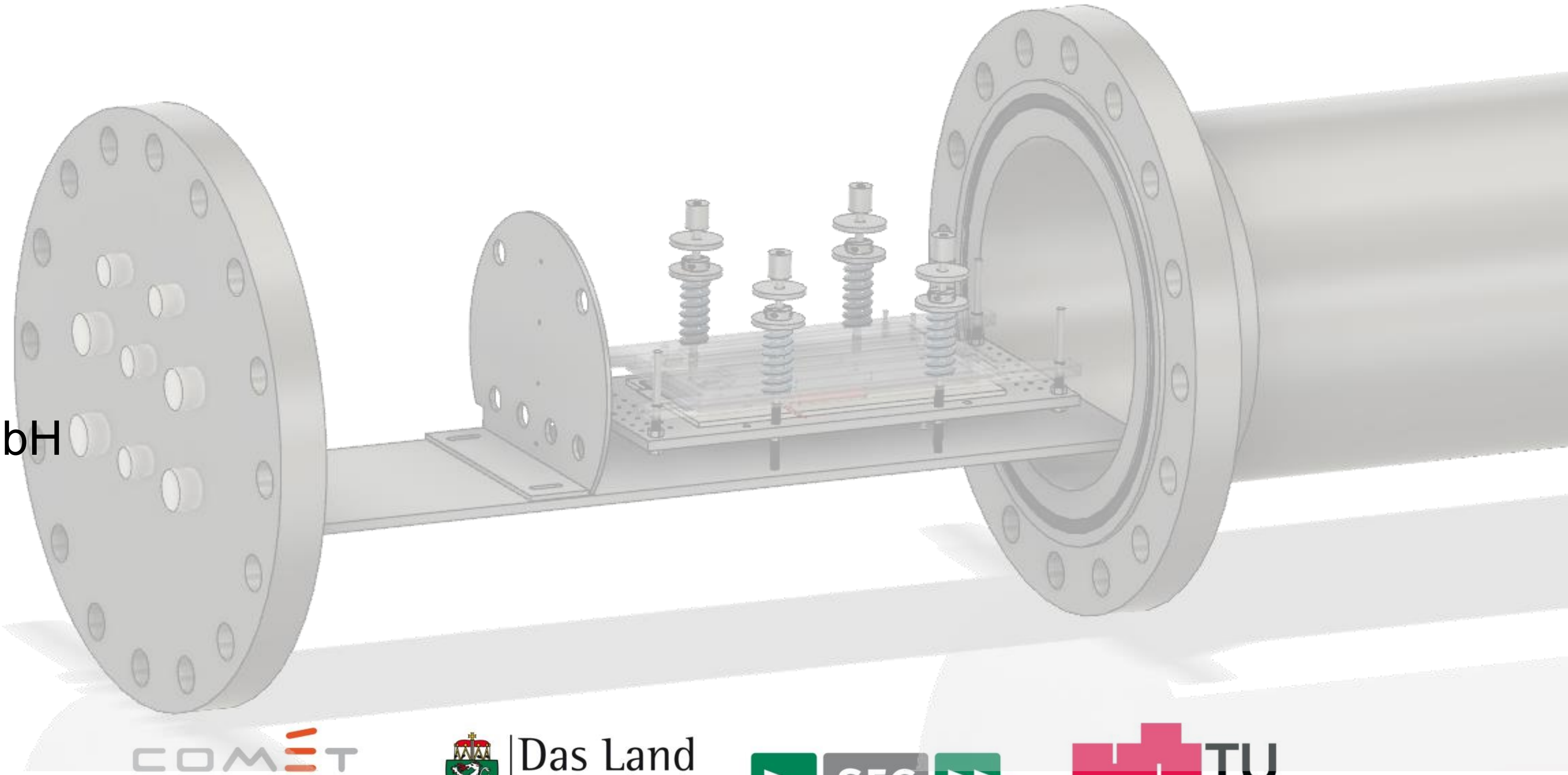
- n_v (mol or liter) the total amount of released gas (in STP: 298.15 K, 100 kPa)
- n_{v1} (mol) the amount of gas produced starting at T_{cell}^{v1} and ending at the T_{cell}^{v2}
- n_{v2} (mol) the gas produced after T_{cell}^{v2} and during the TR
- n_{ch} (mol/s or l/s) the characteristic venting rate based on the minimal duration Δt50% (s) when 50% of the venting gas nch50% (mol) is produced.

BATTLAB THERMAL RUNAWAY TEST BENCH

virtual vehicle

Influencing factors

VIRTUAL VEHICLE Research GmbH



bmvit Bundesministerium für Verkehr, Innovation und Technologie

bmwfw Bundesministerium für Wissenschaft, Forschung und Wirtschaft

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TU Graz Graz University of Technology

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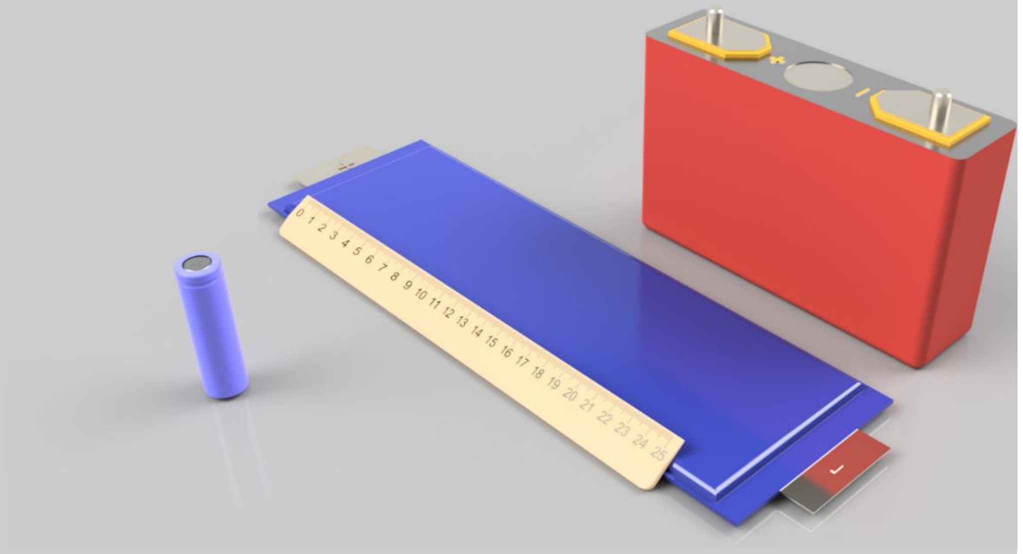
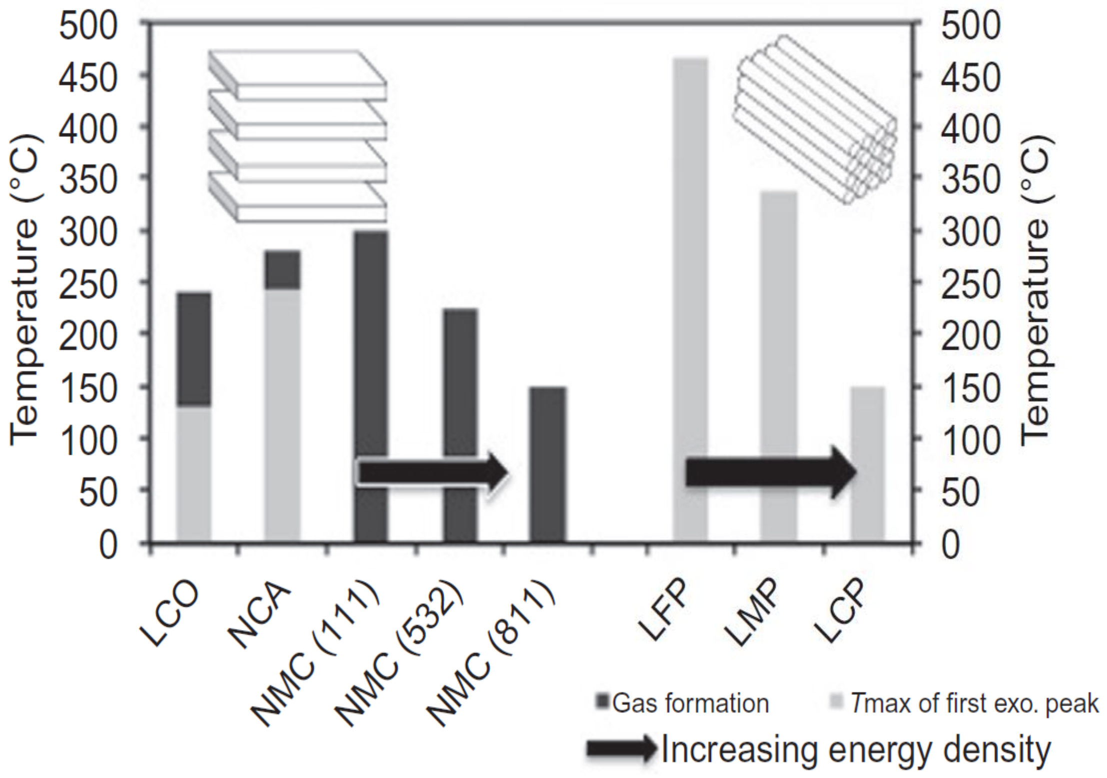
Parameter	today's focus
• **Cell chemistry**	– NMC – Graphite
• **State of charge**	– 100%, 30%, 0%
• **Trigger**	– overtemperature, overcharge, nail-penetration
• **Cell type**	– pouch, prismatic hard case
• **Aging**	– fresh cells, aged cells
• **Gravimetric energy density**	– 170 - 260 Wh/kg
• **Atmosphere**	– N_2



Experiments on cell level

Especially the cathode material influences the thermal stability of a battery and therefore, influences the failing behaviour.

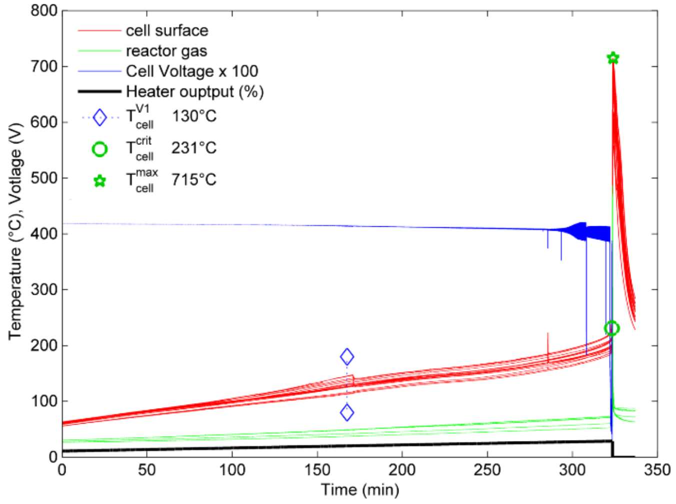


peak temperatures for the first exothermic peak and the gas formation (decomposition temperature for several cathode materials (in case of NMC gas formation temp. = first exothermic peak)

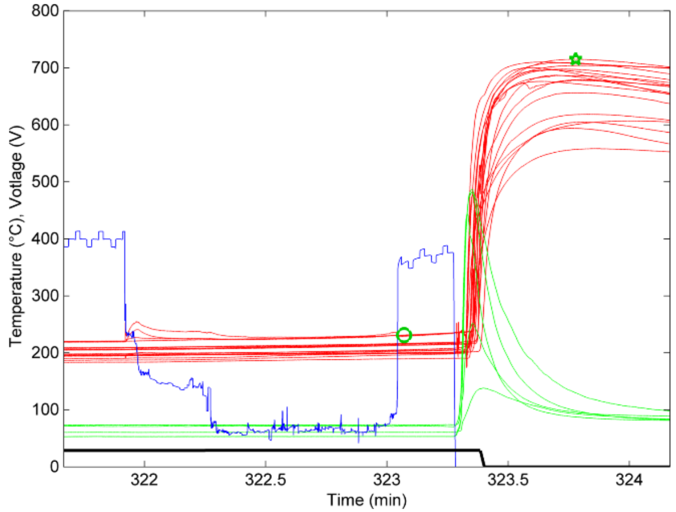
Source: Meike Fleischhammer. 7B - Risk Potentials by Materials. In Electrochemical power sources. Fundamentals, sys-tems, and applications: Li-battery safety, edited by J. Garche & K. Brandt (Elsevier, Amsterdam, 2019), pp. 167–195.

Influencing factors – state of charge (SOC)

SOC has a clear influence on the failing behavior of LIBs. Higher SOC leads to more violent response. Below a certain SOC - no TR reaction triggerable. This certain SOC is cell specific and depend on the cell chemistry and the energy density.



(a)



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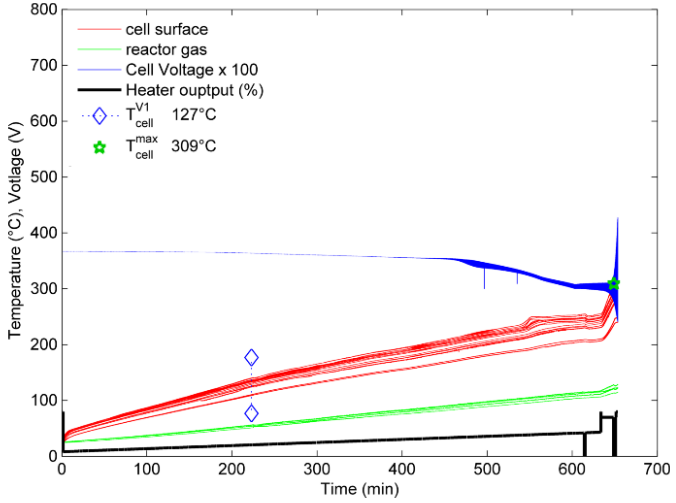

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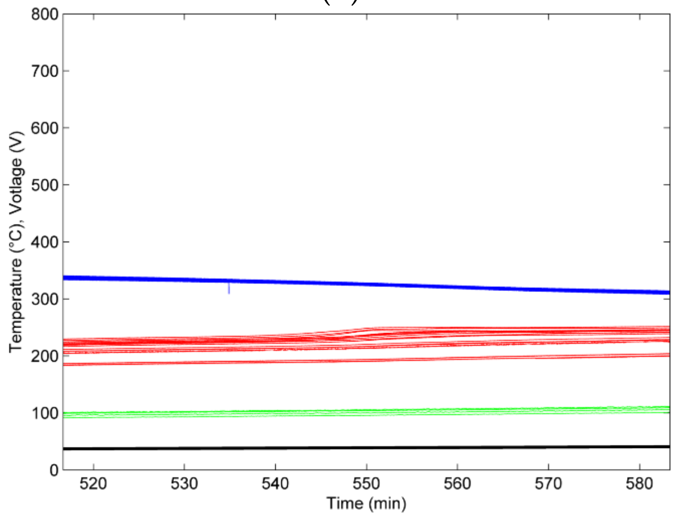

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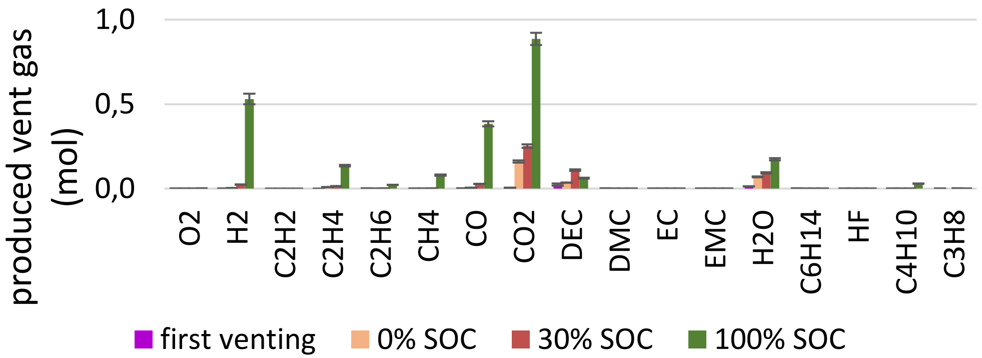
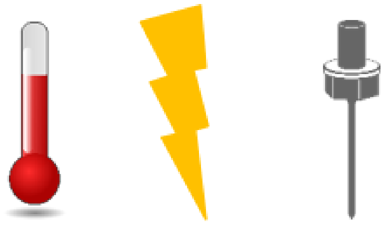
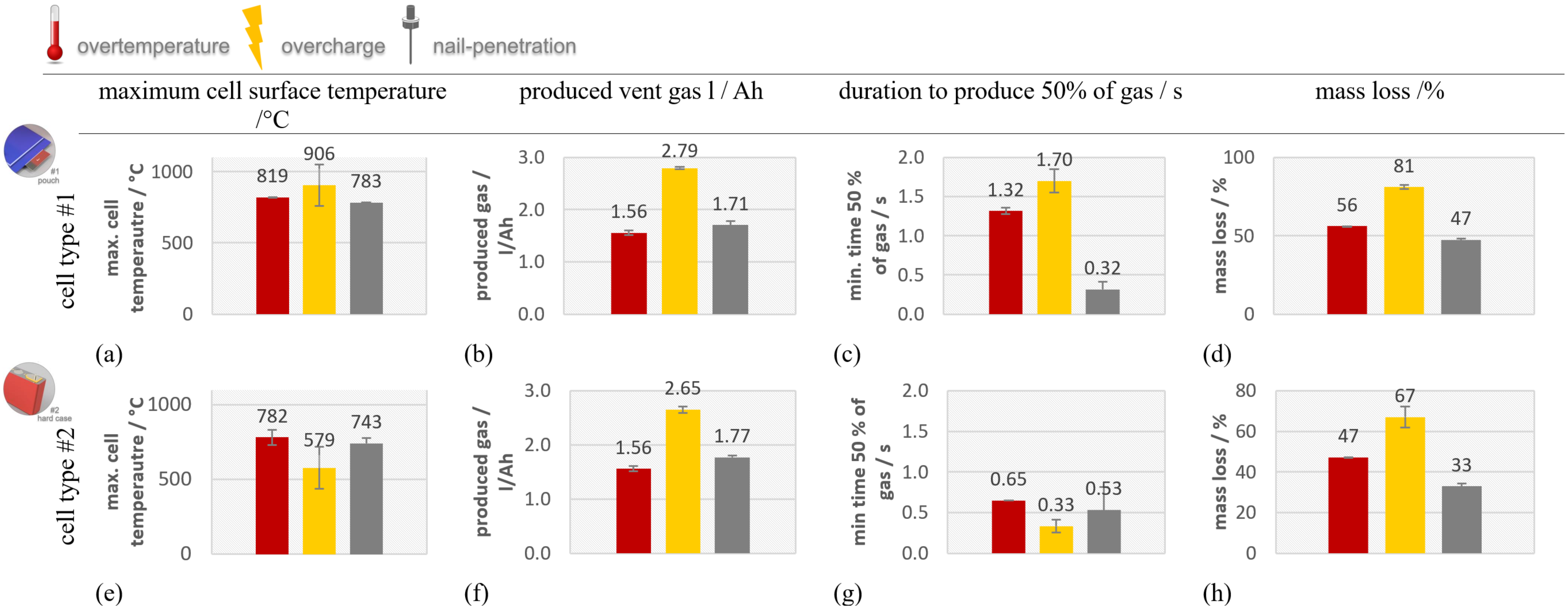


Source: Essl et al. (2020): Batteries 2020; 6(30): 1–28. DOI: 10.3390/batteries6020030

Influencing factors – trigger type

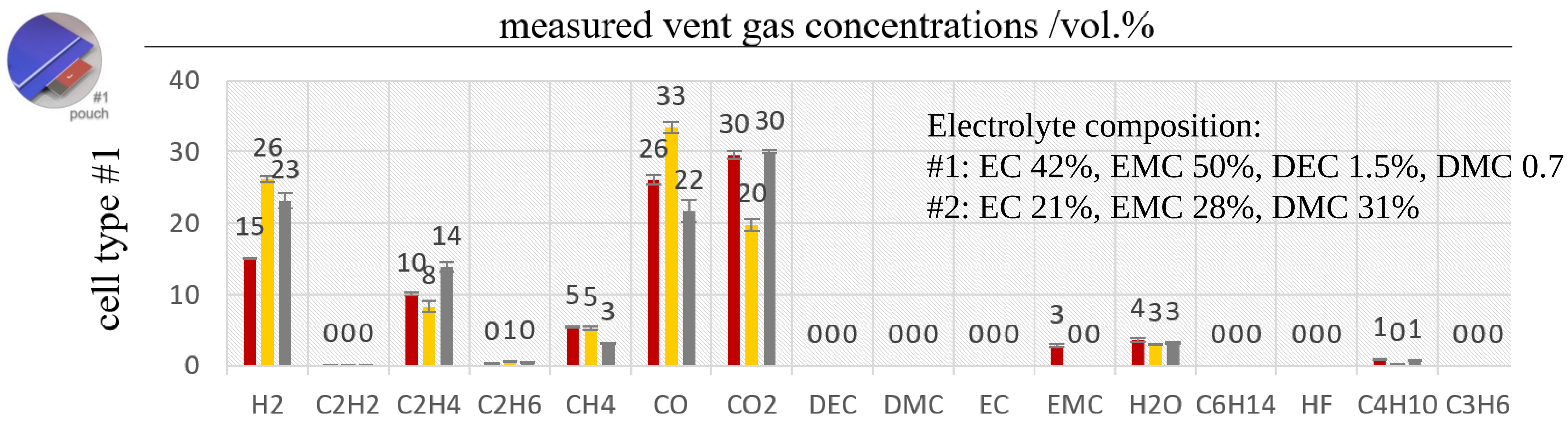


- Overcharge trigger has the highest impact - higher amount of vent gas, a higher mass loss, gas components shifted towards higher H_2 and CO
- First venting observed for overtemperature and overcharge, not for nail-penetration

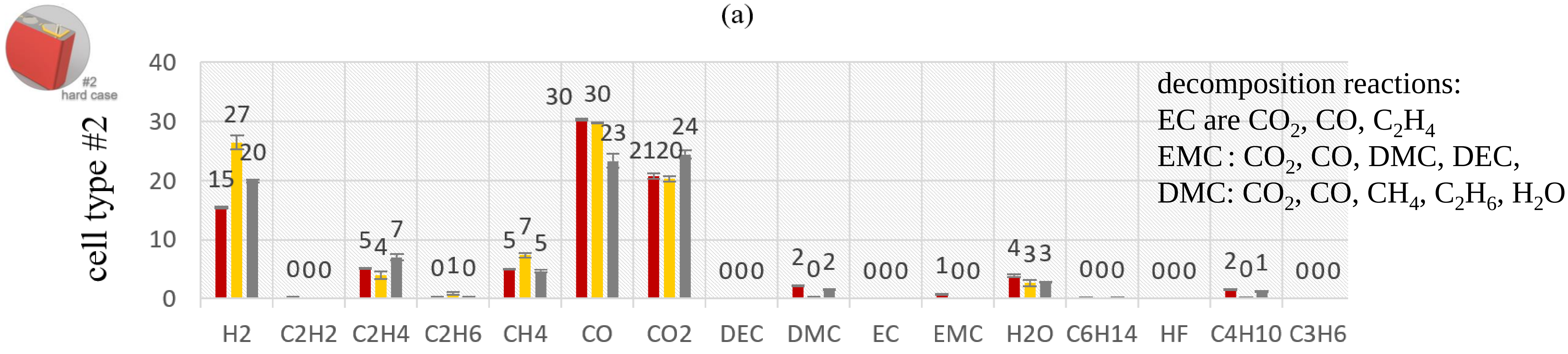


Source: Essl et al. (2020): *Journal of The Electrochemical Society 2020; 167: 130542. DOI: 10.1149/1945-7111/abbe5a*

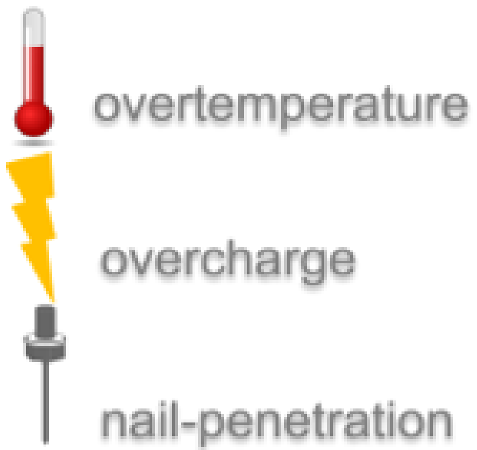
Influencing factors – trigger type



(a)

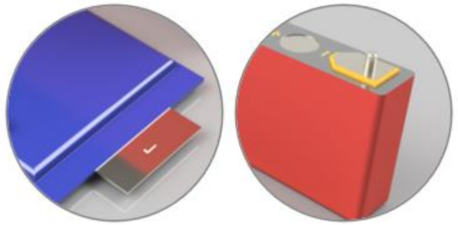


(b)

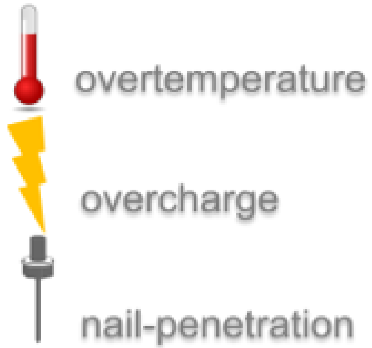


Source: Essl et al. (2020): *Journal of The Electrochemical Society 2020; 167: 130542. DOI: 10.1149/1945-7111/abbe5a*

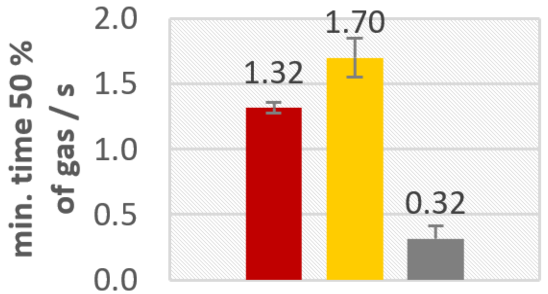
Influencing factors – cell type



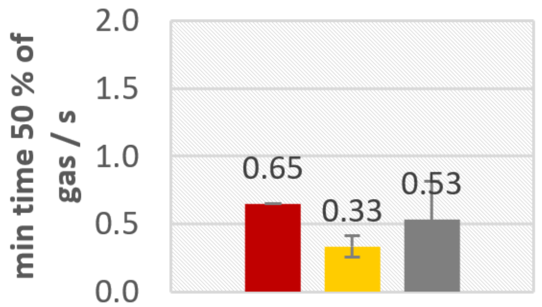
- First venting, TR duration, n_{ch} depends on cell construction – pouch cell opened in OT earlier at a lower surface temperature than the hard case cell, TR started later
- Main characteristics (gas amount, T, gas composition) are the same for both cell types



duration to produce 50% of gas / s



(c)

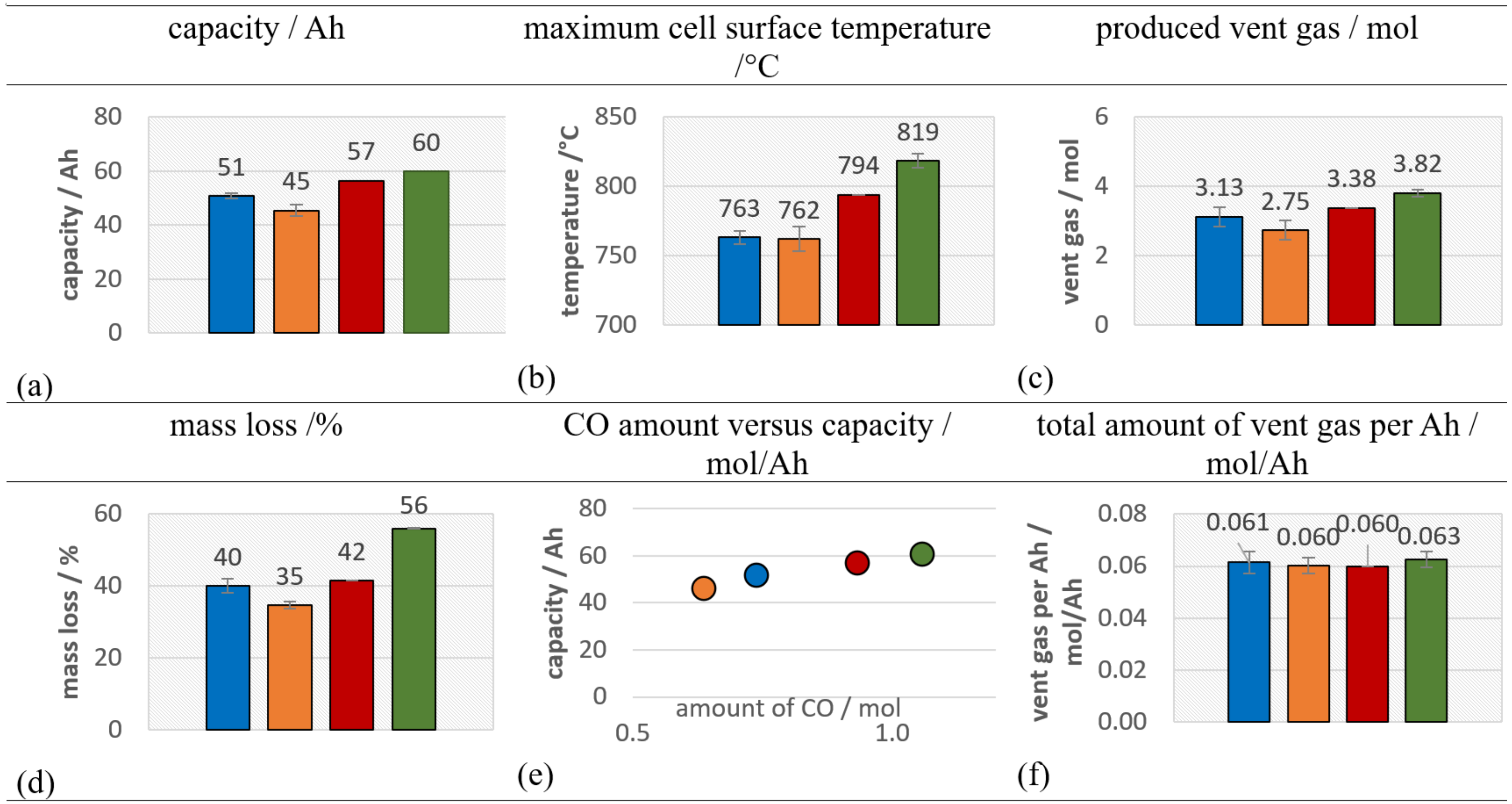


(g)

Source: Essl et al. (2020): *Journal of The Electrochemical Society 2020; 167: 130542. DOI: 10.1149/1945-7111/abbe5a*

Influencing factors – aging

- Reduced TR reaction: Less gas, reduced CO amount, lower maximal temperatures, lower mass loss
- Increased thermal stability for cy+45 and ca60, but not cy-10
- Remaining capacity is decisive for the reaction and safety relevant parameters

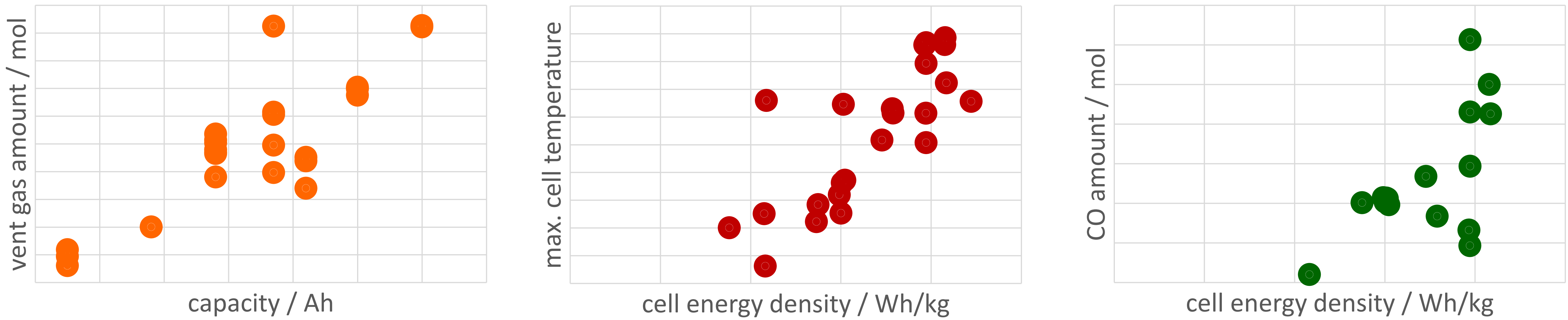


- ! Fresh metallic Li-plating might lead to a more severe TR reaction !

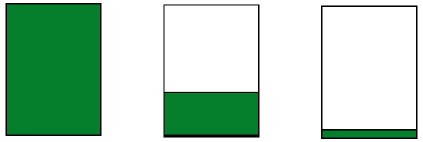
Source: Essl et al. (2021): *Batteries 2021; 7(2), 23. DOI: 10.3390/batteries7020023*

There is a correlation between the stored energy inside a cell and the failing behavior:

- Linear correlation between capacity and amount of produced vent gas (increased capacity – higher amount of vent gas)
- Correlation between energy density and maximum reached temperatures as well as CO amount in the vent gas

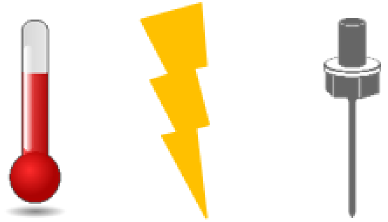


Battery Safety Influencing Factors



SOC:

- SOC is decisive for the failing reaction of batteries – store & transport cells at low SOC
- No TR below SOC_{crit}
- Increased SOC → more severe reaction



Trigger:

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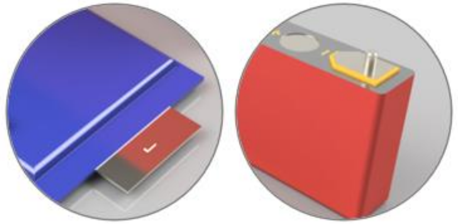


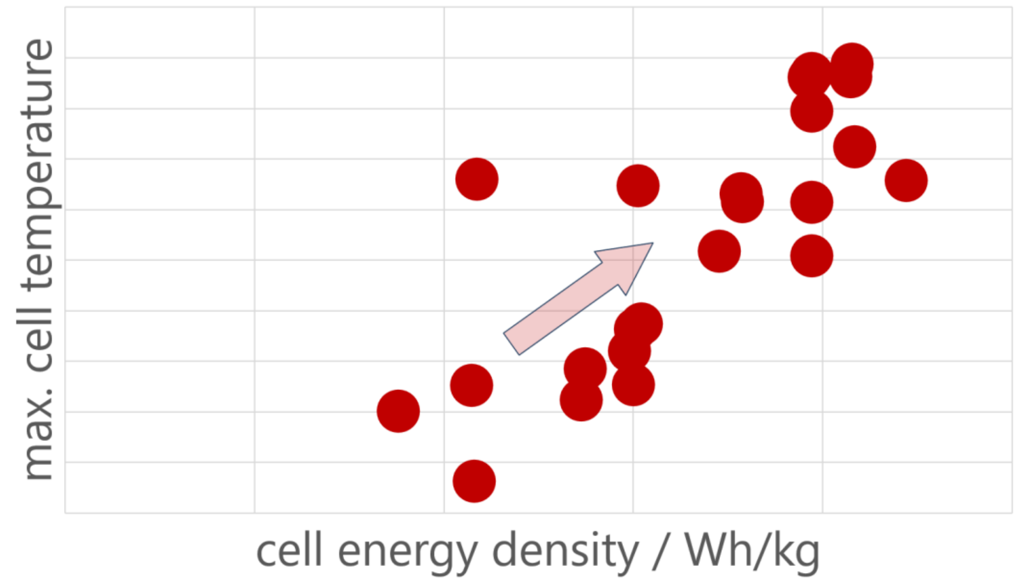
Cell type:

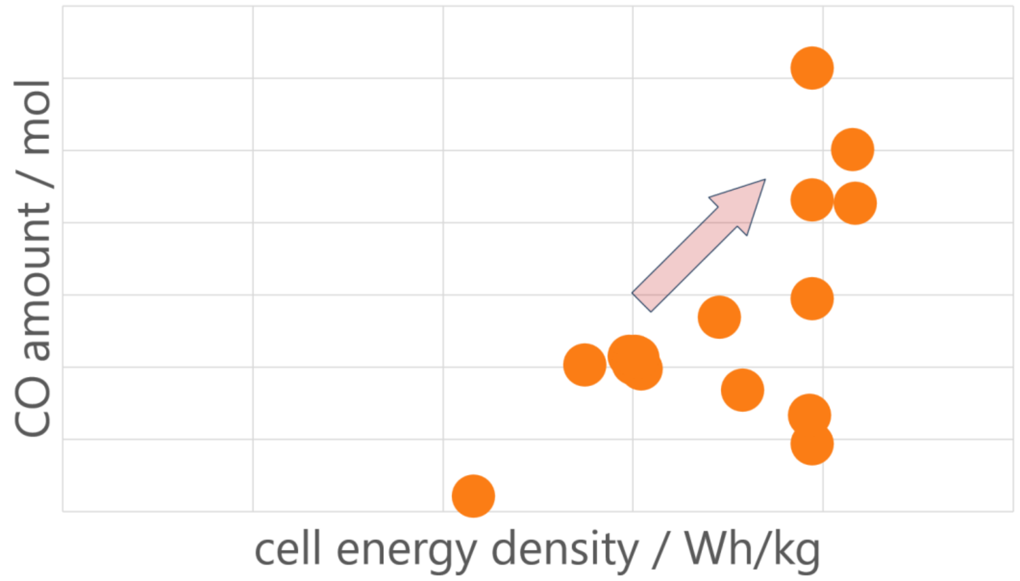
- First venting, TR duration, n_{ch} depends on cell construction – pouch cell opened in OT earlier at a lower surface temperature than the hard case cell, TR started later
- Main characteristics (gas amount, T, gas composition) are the same for both cell types

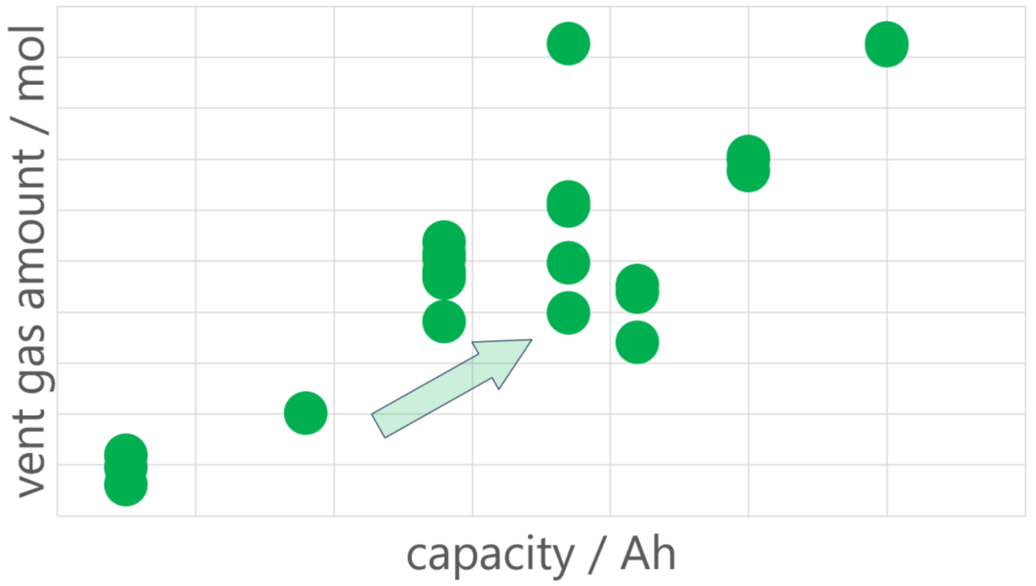
Aging:

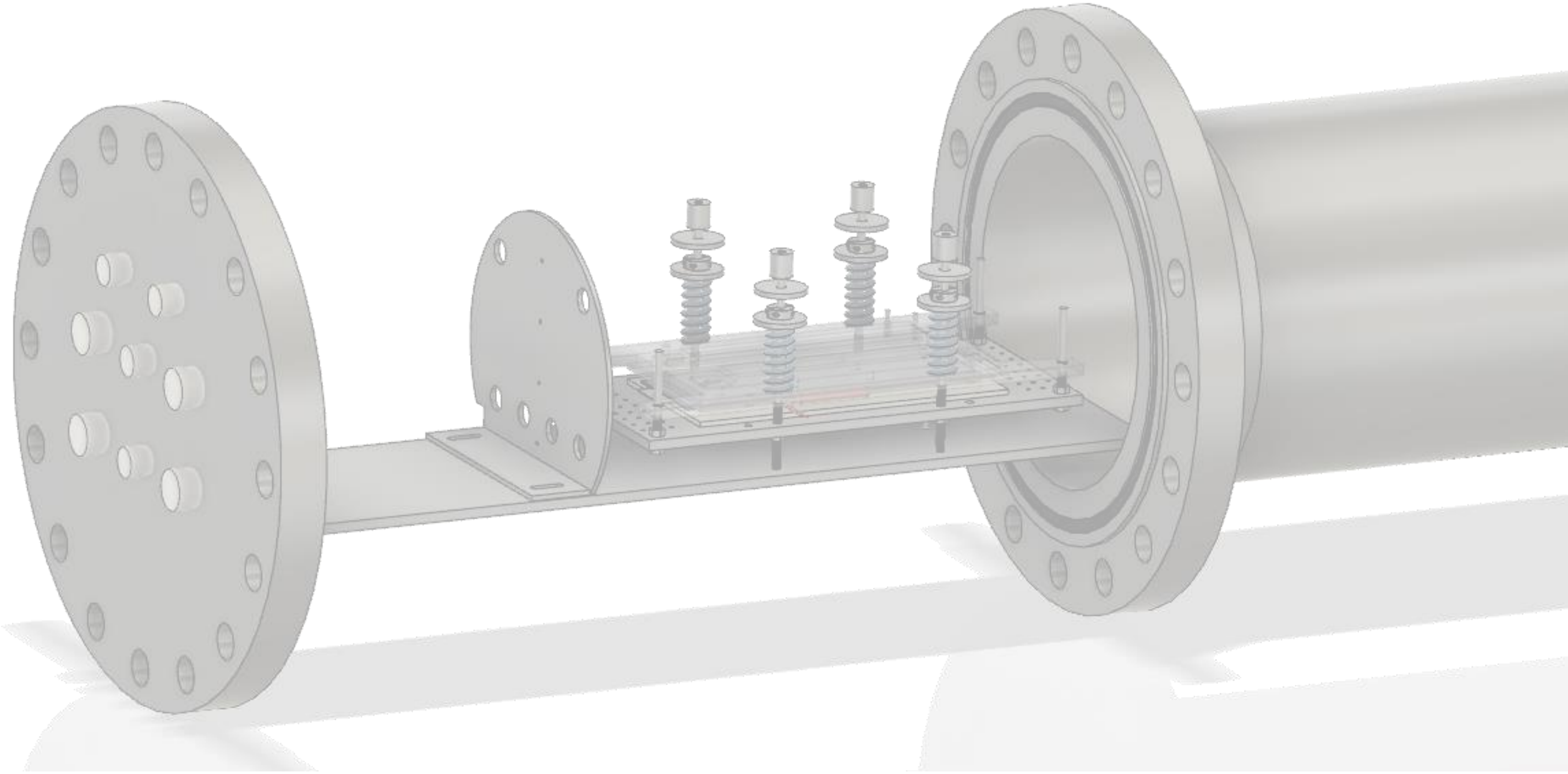
- Reduced TR reaction: Less gas, reduced CO amount, lower maximal temperatures, lower mass loss
- Increased thermal stability for cy+45 and ca60, but not cy-10
- Remaining capacity is decisive for the reaction and safety relevant parameters

Future perspectives – Ni-rich materials









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Publications - Journal publications

- *Essl C, Seifert L, Rabe M, Fuchs A. Early detection of failing automotive batteries using gas sensors. Batteries 2021; 7, 25. DOI: 10.3390/batteries7020025 .*
- *Essl C, Golubkov AW, Fuchs A. Influence of aging on the failing behavior of automotive lithium-ion batteries. Batteries 2021; 7(2), 23. DOI: 10.3390/batteries7020023.*
- *Essl C, Golubkov AW, Fuchs A. Comparing Different Thermal Runaway Triggers for Two Automotive Lithium-Ion Battery Cell Types. Journal of The Electrochemical Society 2020; 167: 130542. DOI: 10.1149/1945-7111/abbe5a.*
- *Essl C, Golubkov AW, Thaler A, Fuchs A. Comparing Different Thermal Runaway Triggers for Automotive Lithium-Ion Batteries. ECS Transaction 2020; 237th ECS Meeting: A02-0436.*
- *Essl C, Golubkov AW, Gasser E, Nachtnebel M, Zankel A, Ewert E, Fuchs A. Comprehensive hazard analysis of failing automotive Lithium-ion batteries in overtemperature experiments. Batteries 2020; 6(30): 1–28. DOI: 10.3390/batteries6020030.*
- *Essl C, Golubkov AW, Planteu R, Rasch B, Thaler A, Fuchs A. Transport of Li-Ion Batteries: Early Failure Detection by Gas Composition Measurements. 7th Transport Research Arena, Vienna, Austria: 2018. DOI: 10.5281/zenodo.1491360.*
- *Golubkov AW, Planteu R, Rasch B, Essl C, Thaler A, Hacker V. Thermal runaway and battery fire: comparison of Li-ion, Ni-MH and sealed lead-acid batteries. 7th Transport Research Arena, Vienna, Austria: 2018. DOI: 10.5281/zenodo.1491317.*
- *Golubkov AW, Scheikl S, Planteu R, Voitic G, Wiltsche H, Stangl C, et al. Thermal runaway of commercial 18650 Li-ion batteries with LFP and NCA cathodes - Impact of state of charge and overcharge. RSC Advances 2015; 5(70): 57171–57186. DOI: 10.1039/c5ra05897j.*
- *Golubkov AW, Planteu R, Krohn P, Rasch B, Brunnsteiner B, Thaler A, et al. Thermal runaway of large automotive Li-ion batteries. RSC Advances 2018; 8(70): 40172–40186. DOI: 10.1039/C8RA06458J.*
- *Golubkov AW, Fuchs D, Wagner J, Wiltsche H, Stangl C, Fauler G, et al. Thermal-runaway experiments on consumer Li-ion batteries with metal-oxide and olivin-type cathodes. RSC Advances 2014; 4(7): 3633–3642. DOI: 10.1039/c3ra45748f.*

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