Studies on early detection of Thermal Runway and Thermal Propagation

Studies conducted by EFZN & HORIBA-MIRA
on behalf of ACEA

Introduction

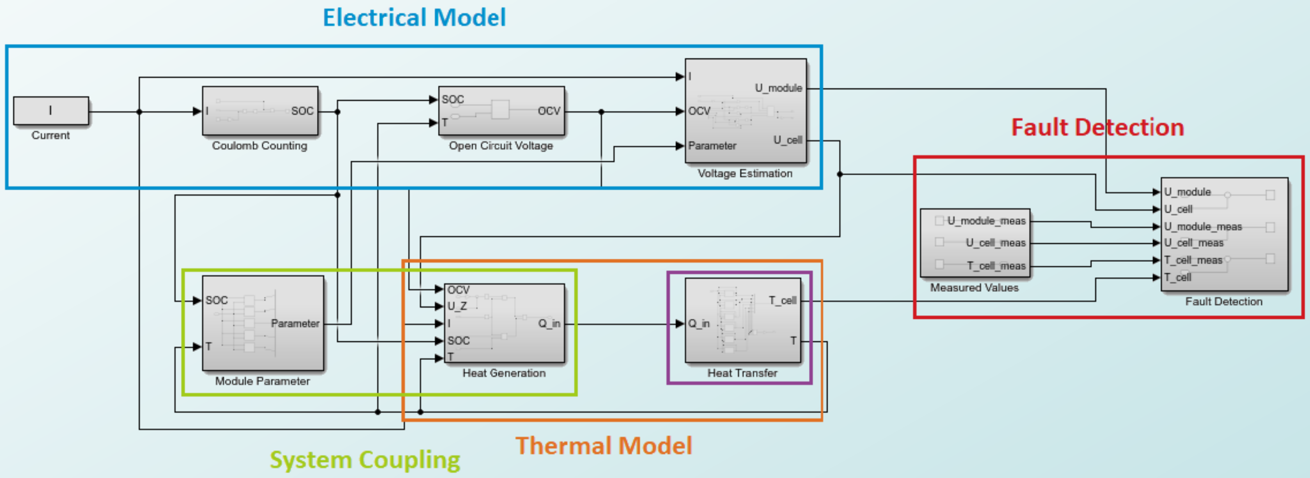
- In 2020 the Energy Research Center of Lower Saxony (EFZN) & HORIBA MIRA (HM) conducted independent studies on the early detection of thermal runaway and thermal propagation
- The conclusion of both studies indicate that early detection of Thermal Runaway and Thermal Propagation is possible

Model-based detection

Electrical Model:
- ➢ Estimates electric behaviour of module in 3 sub-function blocks
- ➢ SOC based on load current calculated with Coulomb-Counting method
- ➢ OCV estimated based through SOC-OCV relationship
- ➢ Module voltage and cell voltage calculated by last block

Thermal Model:
- ➢ Calculates heat generation and heat dissipation
- ➢ After estimating individual cell temperatures, module temperature is approximated by averaging each temperature
- ➢ This value is used as reference for parameter in look-up table and in reversible heat calculation

System Coupling:
- ➢ Coupling in two ways:
  1. module parameter and heat generation
     - ➢ Connects module temperature to electric behaviour based on temperature dependency
  2. electrical state of cell and thermal behaviour
     - ➢ by causing heat generation during operation



Fault Detection:
- ➢ Estimates absolute difference between input signals to be compared
- ➢ Output signals cell voltage and module voltage are compared against measured cell and module voltage from block diagram measured values for fault detection
- ➢ Modelled cell temperatures are also observed and compared to measured cell temperatures
- ➢ By calculating absolute difference in both parameter, fault signal is generated if the absolute difference exceeds a threshold

Fault detection based on module and cell voltages, temperatures and heating rates

Local heating

- local heating with glow plug during two WLTP cycles and an intermediate charging phase after the first WLTP cycle.
- local heating triggers the thermal runaway.
- module is treated with complete WLTP cycle with the same C-rate as for the surface heating
- afterwards charged for 15 min with a C-rate of 1
- followed by a second WLTP cycle.
- glow plug, positioned between cell 3 and 4, manually regulated in steps to 250, 500, 700, 850 and 1000 °C.
- heating starts after around 3000 s (i.e. 5 min after the start of the second WLTP cycle)
- trigger deactivated when thermal runaway has started and at least one cell of the module is under flames.

Result

- Detection through module voltage was not possible
- Cell voltages and temperatures are suitable for early detection
- Module could even detect faults within safe operating range, which would not be possible with standard BMS software

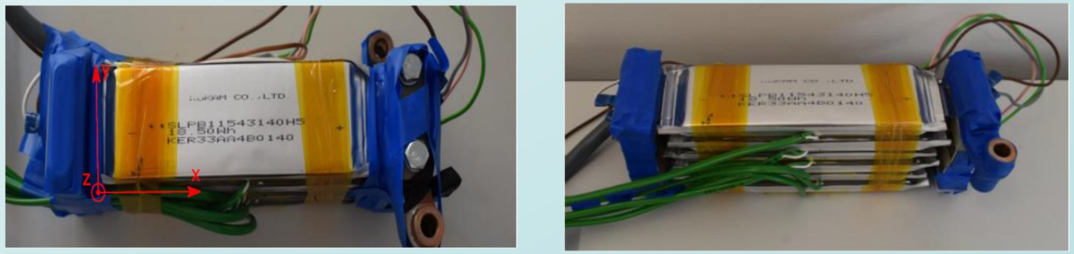
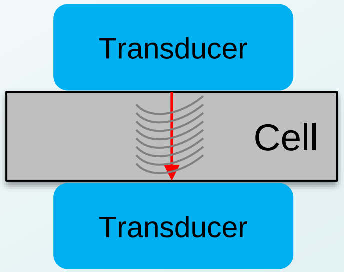


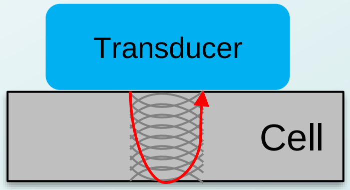
Figure 1: Assembled 6S1P-module with integrated temperature and voltage sensors (left). Additionally the xz-plane view from the lithium-ion module with the position of the temperature sensors (green wires) between the cells is given on the right side (see also Figure 19 in the Appendix). From top to bottom the sensors are numbered from 1 to 6.

TP detection via ultrasounds

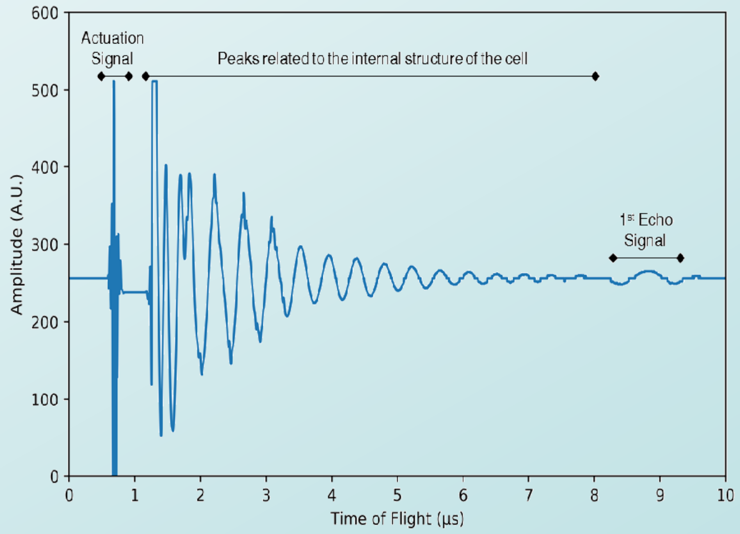
- transmission of ultrasonic pulse through the cell
- signal received by second transducer on the other side of the cell (transmission mode), or
- reflected signal can be monitored by same transducer (pulse-echo mode).
- amplitude and time for the signal to reach the receiving transducer, the time of flight (ToF), depends on the thickness, density and elastic modulus of the material
- pulse-echo mode gives insight on change to material properties, e.g. SoC or SoH

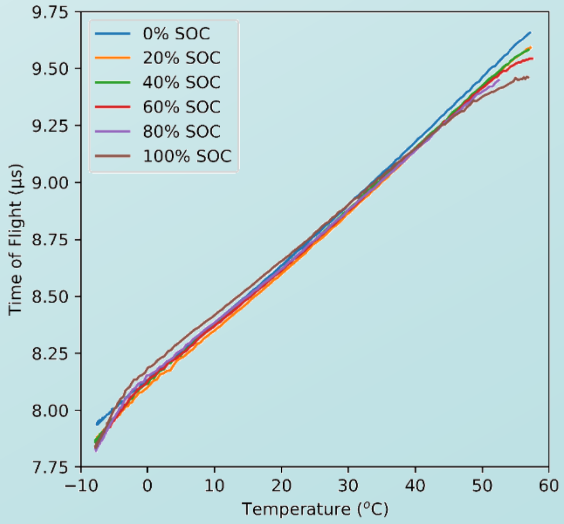


Transmission mode



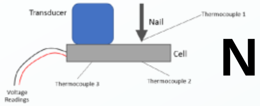
Pulse-echo mode





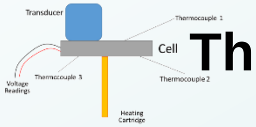
SoC: State of Charge
SoH: State of Health

Ultrasounds reliably detect failure in various setups



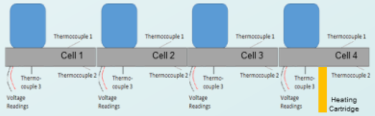
Nail Penetration

- acoustic monitoring is highly sensitive to structural damage by nail penetration



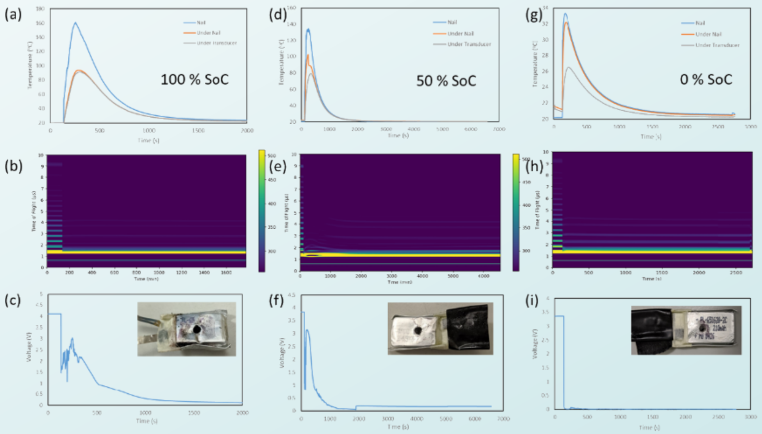
Thermally-induced heating

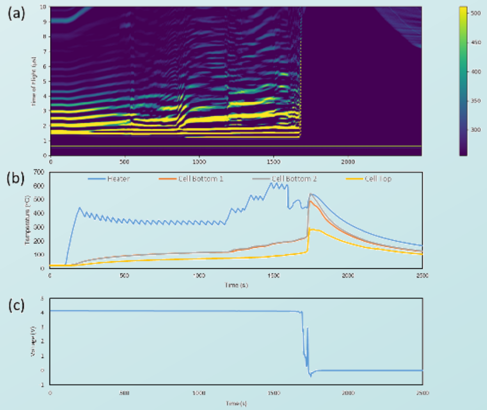
- Changes in ToF of first echo peak correlate with cell temperature giving clear indication that the cell is heating
- Electrolyte evaporation occurs well in advance of cell failure results in loss of acoustic signal

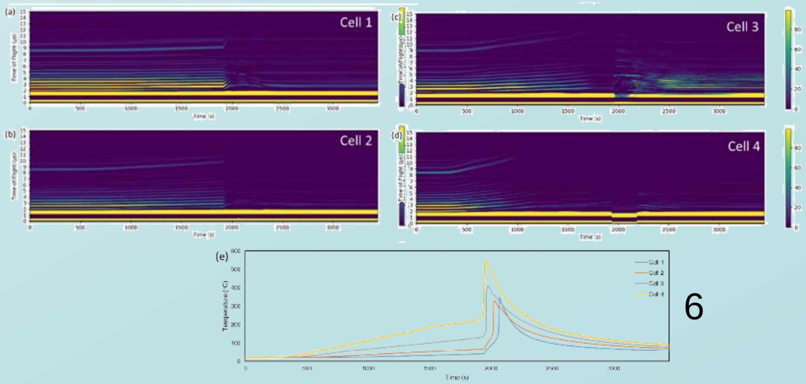


Module test

- Using multiple transducers detection of propagation of TR through a small module of cells
- Indications that cells were reaching dangerous temperatures evident from acoustic measurements long before first cell failure







Conclusions from lab ”module” test

Predictive modelling detection

- Successful detection of safety related cell fault 360 s before onset of TR using cell voltage as metric
  - Requires voltage measurement on cell level
  - Detailled parameterization of the model is a prerequisite
  - Cell is in normal operating temperature range when fault is detected
- Potential for further improvements in the predictive model
  - Including additional signals
  - Expanding and adapting the model to account for mechanical and electrical triggers

Ultrasonic detection

- Accoustic signals indicating cell changes consistent with a thermal event cell were observed more than 900 s before TR by monitoring changes to flight (ToF)
  - Accoustic changes observed during failure were significantly larger than what was observed during normal conditions
  - Cell is in normal operating range when the first thermal damage is detected
- Consistent test results for 4 conditions studied: nail penetration, over-current, homogeneous heating and local heating

List of companies and institutions that are developing thermal runaway and thermal propagation early detection systems (not exhaustive)

Company	Location	Web Page	Specialty
Batemo	Karlsruhe, Germany	www.batemo.de	Modelling
CIDETEC Energy Storage	San Sebastián/Donostia, Spain	www.cidetec.es	Modelling
Titan Advanced Energy Solutions	Somerville, MA, U.S.A.	www.titanaes.com	Ultrasound
CAMX Power	Lexington, MA, U.S.A.	www.camxpower.com	Short detection and monitoring product
Fraunhofer Institute for Silicate Research ISC	Würzburg, Germany	www.isc.fraunhofer.de	Ultrasound
ISEA, RWTH Aachen University	Aachen, Germany	www.isea.rwth-aachen.de	Ultrasound and Impedance Spectroscopy
Nanyang Technological University (NTU Singapore) und KVI Battery	Singapore, Singapore	www.ntuitive.sg	Battery Enthalpy and Entropy Measurements
Qnovo	Newark, CA, U.S.A.	https://qnovo.com/	Impedance spectroscopy and adaptive modelling
Vitesco Technologies	Regensburg, Germany	www.vitesco-technologies.com/en/	Gas sensor

Back-up

EFZN

efzn
Energie-Forschungszentrum Niedersachsen
EST
Forschungszentrum Energiespeic

Thermal Runaway and Thermal Propagation Detection- Module
Supplemented Literature Review

On behalf of
ACEA European Automobile Manufacturers Association
ACEA
Avenue des Nerviens 85
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Goslar, 22 December 2020

efzn
Energie-Forschungszentrum Niedersachsen
EST
Forschungszentrum Energiespeichertechnologien

Thermal Runaway and Thermal Propagation Detection- Module
Final Report

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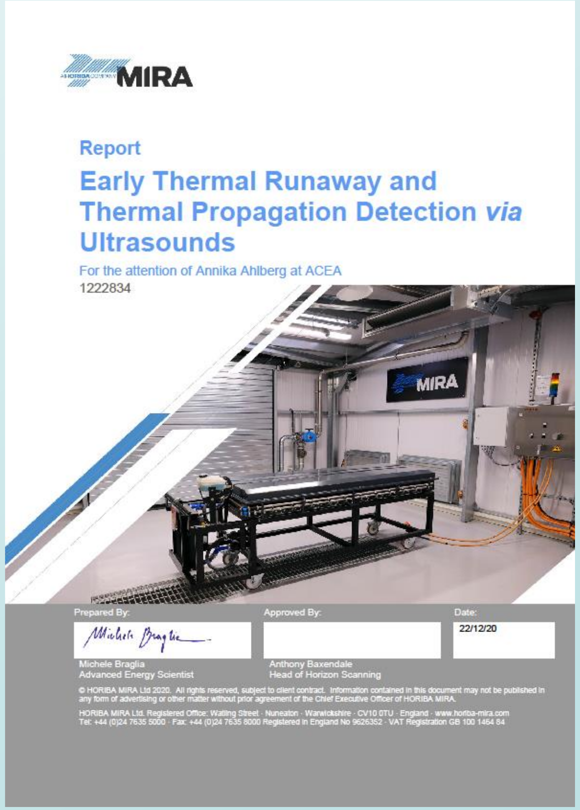
December 2020

HORIBA MIRA



MIRA

Report
Early Thermal Runaway and Thermal Propagation Detection *via* Ultrasounds
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1222834

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