LS-DYNA Navigating around Short-Circuits: Exploring Ansys LS-DYNA's Battery Modelling Capabilities

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Powering Innovation That Drives Human Advancement

Navigating around Short-Circuits

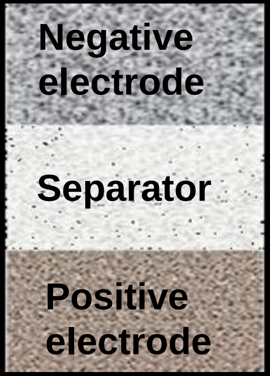
Exploring Ansys LS-DYNA's Battery Modeling Capabilities

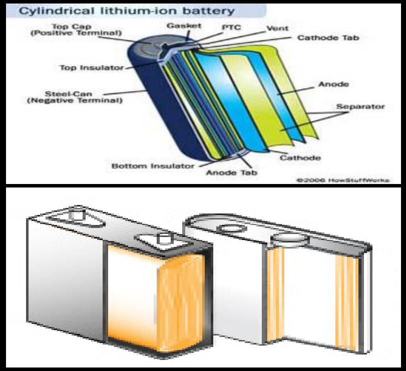
Challenges in electric vehicle battery development

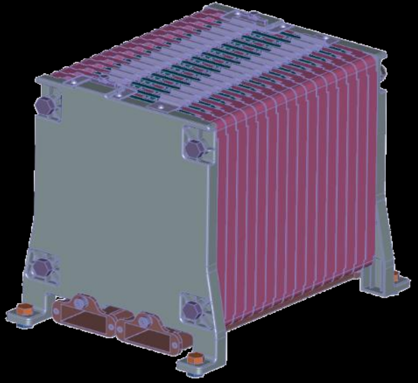
Category	Challenge	Target
Performance	Mileage/Range	400 Miles
	Charging	15 Minutes
	Lifetime	10 Years
Safety	Thermal Reliability	20-40 C
	EMI / EMC	0 % EMI
	Structural Abuse	No Shorts
Economy	Cost	£ 90 / Kwhr
	Controls / Software	30 % Productivity

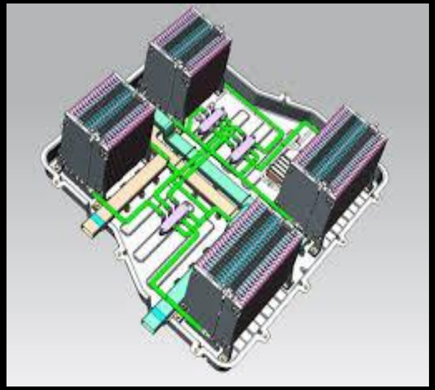
Scale of batteries

Micrometer









Meter

Electrode → **Cell** → **Battery Module** → **Battery Pack** → **Electric Power Train**

Electrode: A unit cell consist of a positive and negative electrode and a separator. The electrode itself consist of an active layer and a current collector

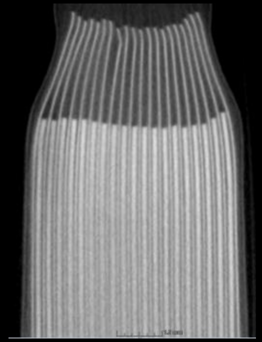
Cell: The layers are wound or stacked to create cylindrical, prismatic or couch cell

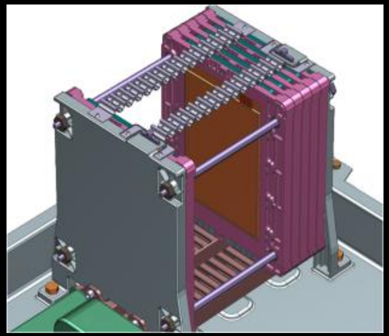
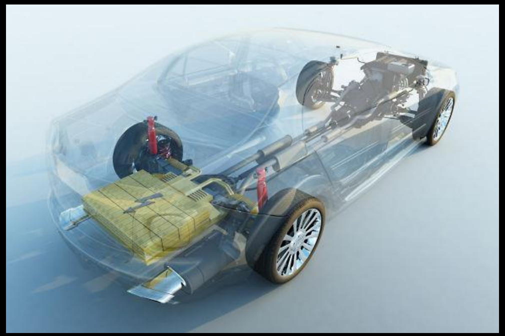
Battery Module: The cells are grouped to form a battery module

Battery Pack: The modules are connected to form a battery pack.

Electric Power Train: The pack is integrated with other components (Power electronics, motors, etc) in EV power train

Aspects on different scales



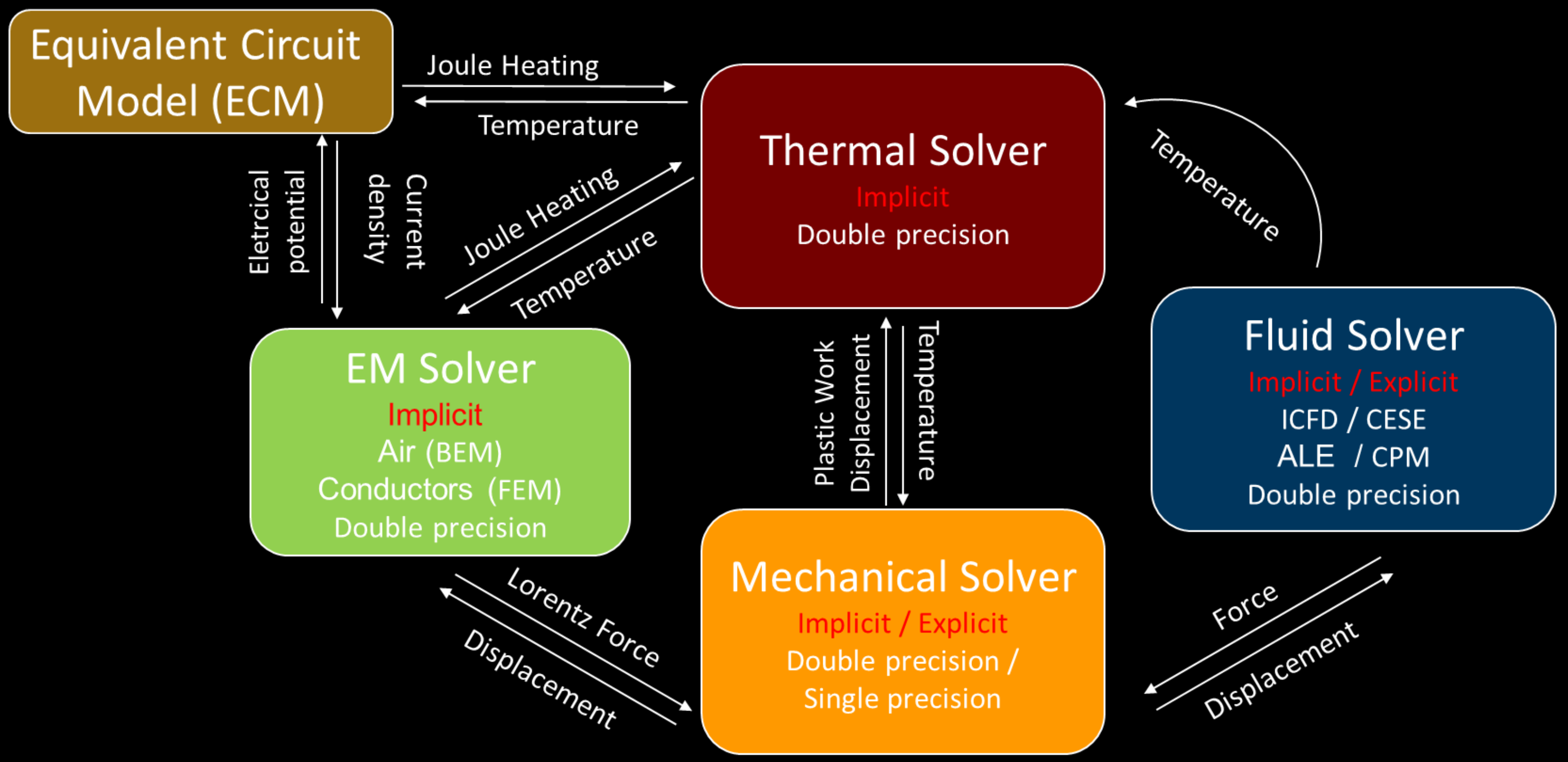
Small → Large

Electrode	Cell	Module/Pack	Powertrain
Layout Process Manufacturing Life	Manufacturing Design Charging / Discharging Heating / Cooling **Safety**	Thermal Management Durability NVH EMI/EMC **Safety**	System Integration Battery Management

History of battery modeling capabilities within LS-DYNA

- 2015–2019 : **Provide numerical predictive tool for mechanical and thermal battery abuse**
  - Collaboration with Ford Motor Company funded by US government
  - Resulted in availability of equivalent circuit models in LS-DYNA
- 2019 : Ansys acquires LSTC
- 2020–2023 : Provide validation and understand workflow on using LS-DYNA for battery development. Internal experimental projects and benchmarks with LS-DYNA
  - Internal experimental project.
  - Collaboration with laboratories -> more experimental tests
  - Positive feedback loop between development, internal and external experts
- 2022-2024 : Extension of applications
  - Swelling
  - Venting
  - Pre- and post-processing

One code strategy and EM solver

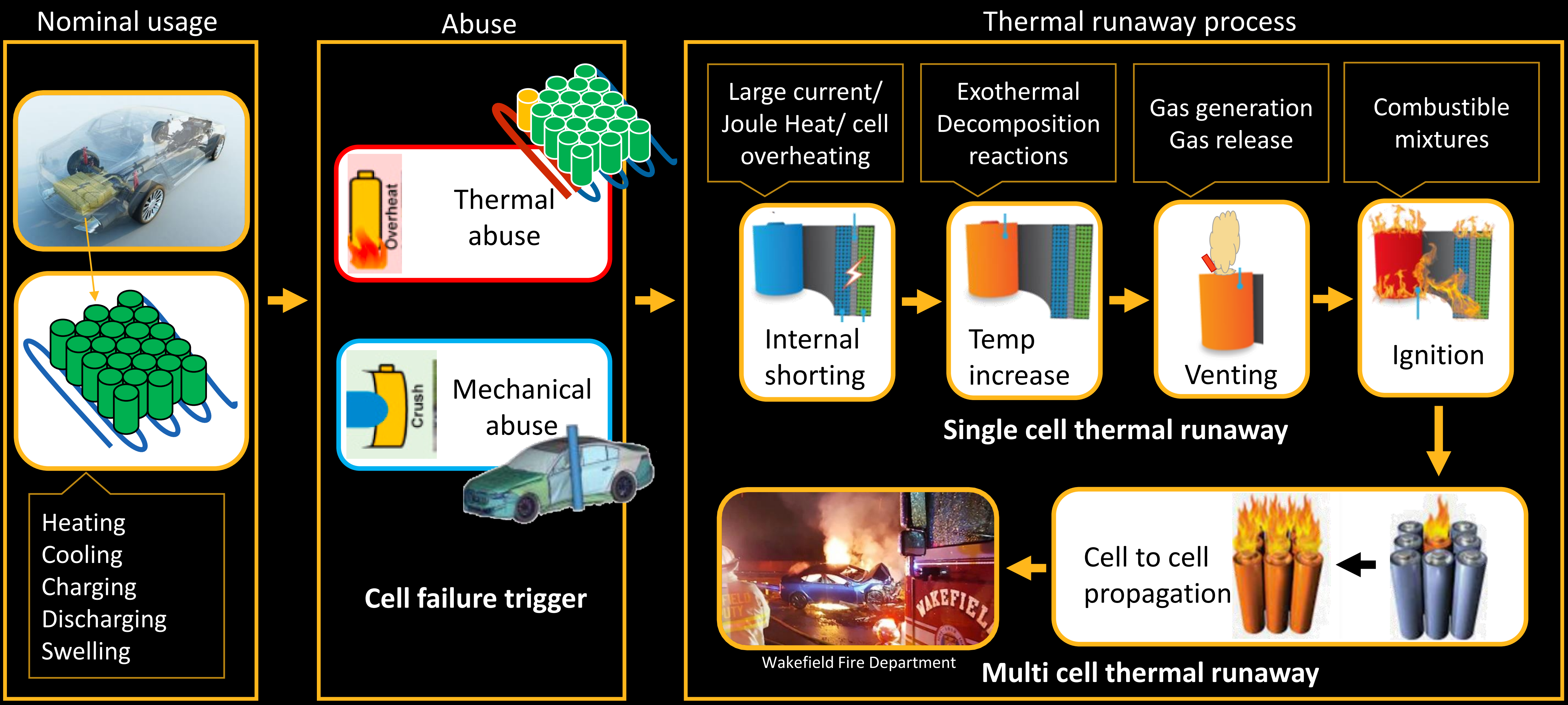


EM
Resistive heating solver

EM solver evolution

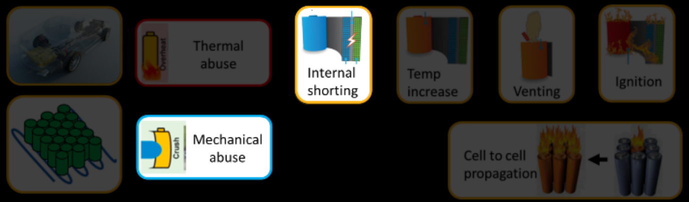
Battery module
R11 : N/A
R12 : First release of BatMac and other Equivalent Circuit Models (ECM).
R13 : Addition of capabilities based on user feedback. E.g. erosion, second order Randles and more.
R14 : Thermal exothermal reaction model.
R15 : Better erosion criteria in solid model. Improvements on the exothermal reaction model. Tabs in shells.

Battery safety and when it turns unsafe

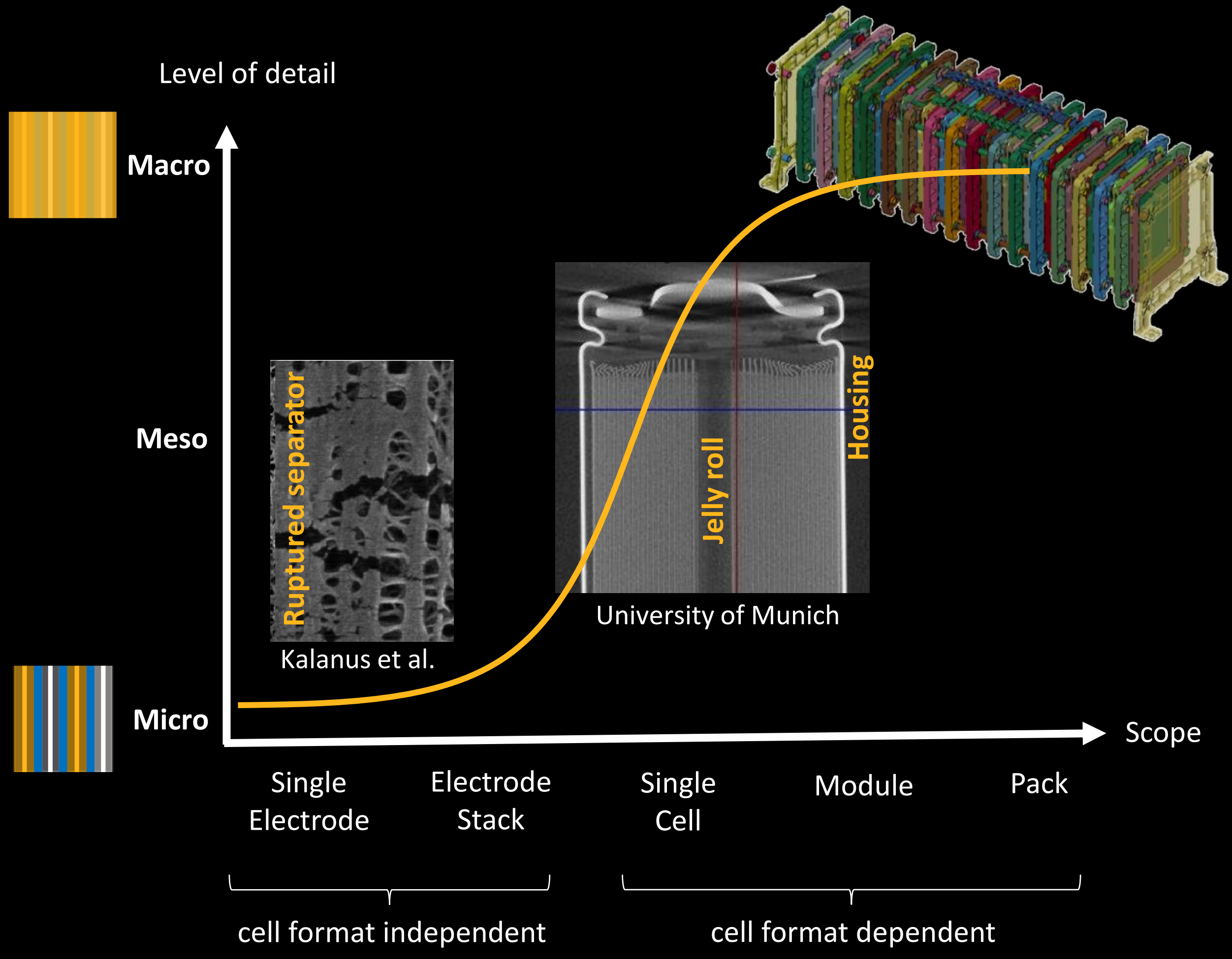


Graphics adapted from Sinovoltaics

Mechanical abuse



- Excessive mechanical load cause, electrodes or separator to rupture
- Models on micro and macro scales to understand mechanical behaviors under indentation or penetration
  - Detailed deformation and failure behaviors of separator, single electrodes up to single cell (micro)
  - Global kinematics of battery modules or single cells to capture interaction with surrounding parts (macro)

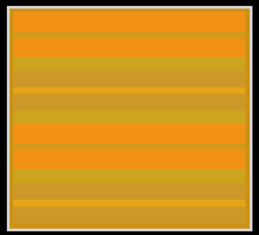


Mechanical failure analysis on micro and macro levels

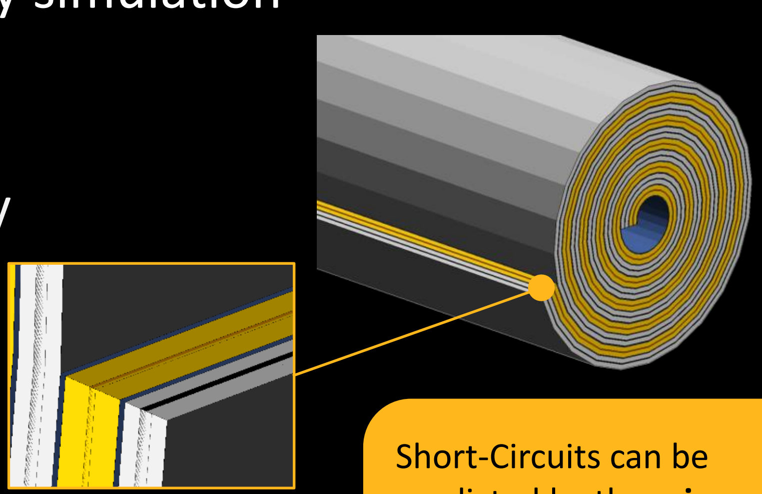
- Physical testing is required to calibrate material models on micro and macro scale
  - Tensile / Compression / Bending / Indentation
- Important characteristics in battery simulation can be considered
  - Compressibility
  - Tension-compression asymmetry
  - Anisotropy
  - Damage and fracture
  - Strain-rate dependency
  - Viscoelasticity
  - State of charge dependency

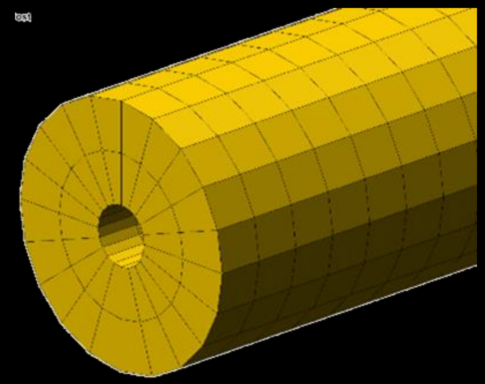
Micro model

Macro model



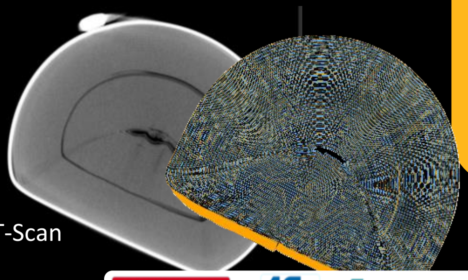
Single/multiple layers represented by a single or few elements





Short-Circuits can be predicted by the **micro model** with an adequate failure criteria of individual layers

Short-Circuits can be predicted by the **macro model** e.g. by correlating failure in tests or the micro model with mechanical quantities



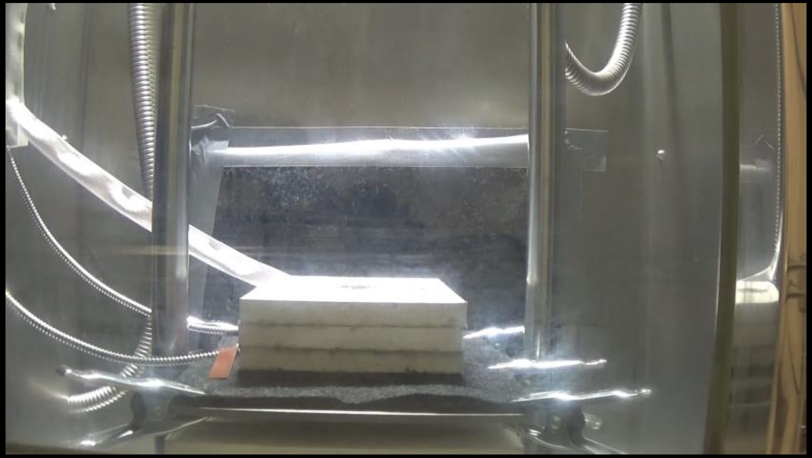
CT-Scan

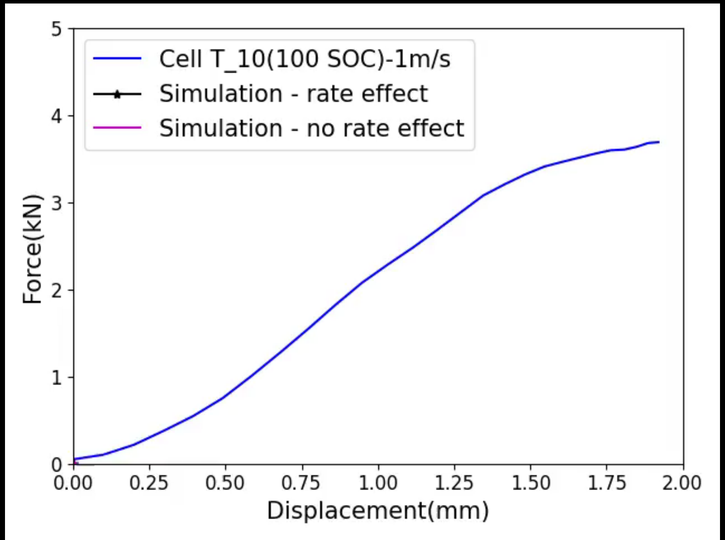
Simulation

COMET-Project

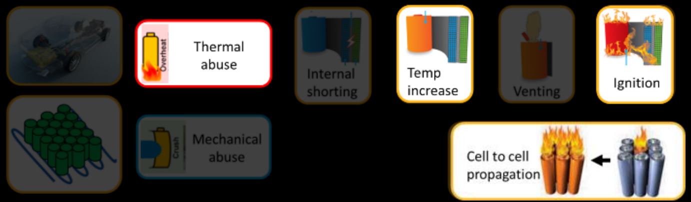
Homogenized mechanical single cell model with anisotropy

- Multi-directional cell mechanical properties with a material failure criteria
- LS-DYNA is capable to simulate cell mechanical response under different loading modes and directions
- On going developments to meet requirements of battery materials
  - Directional strain rate dependency and Poisson's ratio in uncompacted state for MAT_MODIFIED_HONEYCOMB (MAT_126)



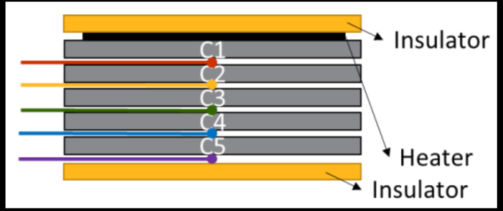


Thermal abuse

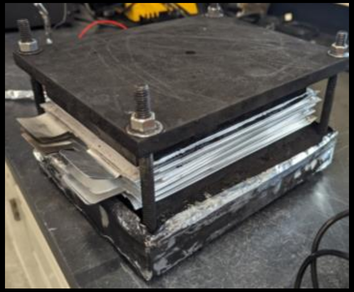


- Excessive temperature causes separator to melt or collapse.
- Physical testing necessary to characterize the thermal abuse
  - Temperature
  - Voltage
  - Pressure

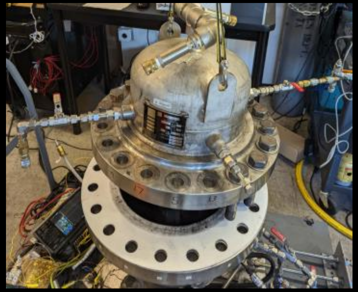
Top cell covered by heat pad and temperature sensor in between

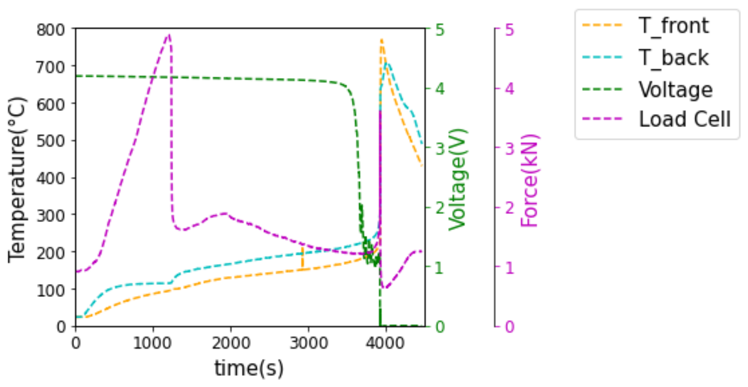


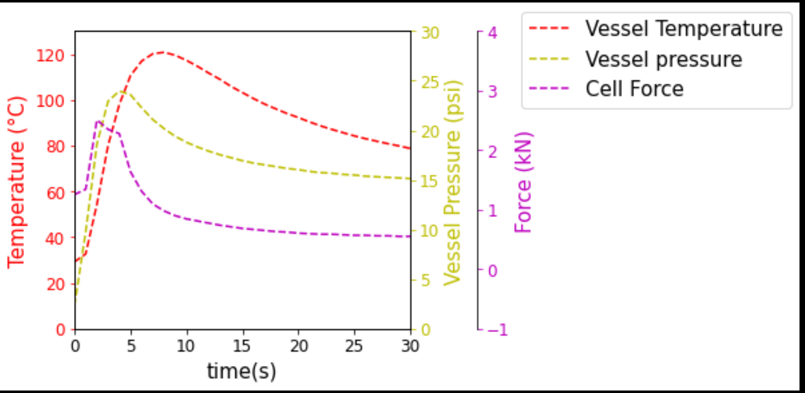
Cell array is fixed between plates



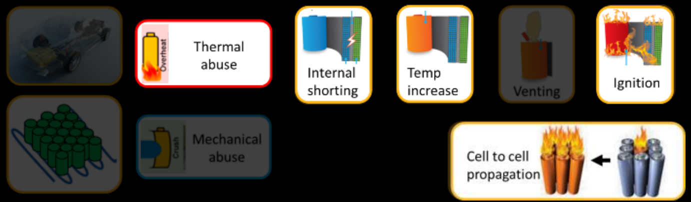
Cell array is placed in pressure chambre







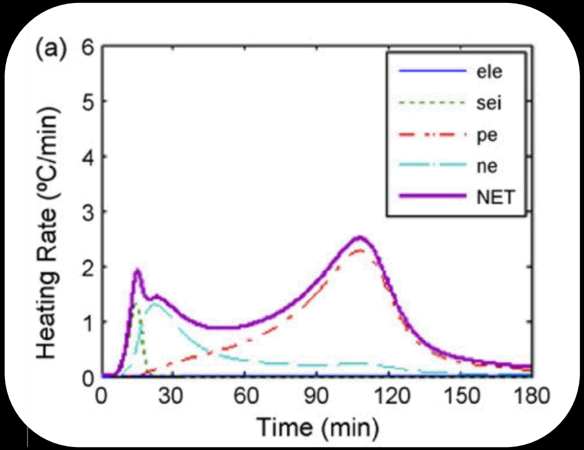
Thermal abuse



- Thermal solver provides possibilities to consider thermal boundaries and properties
  - Heat conduction, convection and radiation
  - Specific Heat capacity
  - Anisotropic thermal conductivity (windings)
  - Contact (cell to cell propagation)
- Thermal short circuit criteria can be defined (EM)
- Exothermal reaction models are available *LOAD_HEAT_EXOTHERMAL_REACTION
- Simplified approach for heating term due to exothermal reaction with *EM_RANDLE_EXOTHERMIC_REACTION

```
*LOAD_HEAT_EXOTHERMIC_REACTION
$     hsid     stype      nsid        bt        dt      tmin      tmax      toff
         1         1
$    csei0      asei     easei      msei      hsei        wc                  ru
      0.151.6670E+151.3508E+05       1.0  257000.0 6.104E+02              8.3140
$     cne0       ane      eane       mne       hne      wcne     tsei0     tseir
      0.752.5000E+131.3508E+05       1.0 1714000.0 6.104E+02     0.033     0.033
$   alpha0       ape      eape    mpep1       hpe       wpe     mpep2
      0.046.6670E+131.3960E+05       1.0  314000.0 1.221E+03       1.0
$      ceo        ae       eae        me        he        we
       1.05.1400E+252.7400E+05       1.0  155000.0 4.069E+02
```

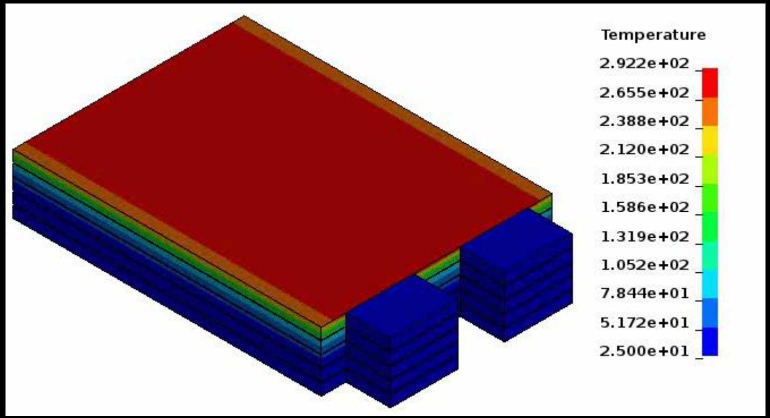
$$S_{\text{abuse\_chem}} = S_{\text{sei}} + S_{\text{ne}} + S_{\text{pe}} + S_{\text{ele}}$$

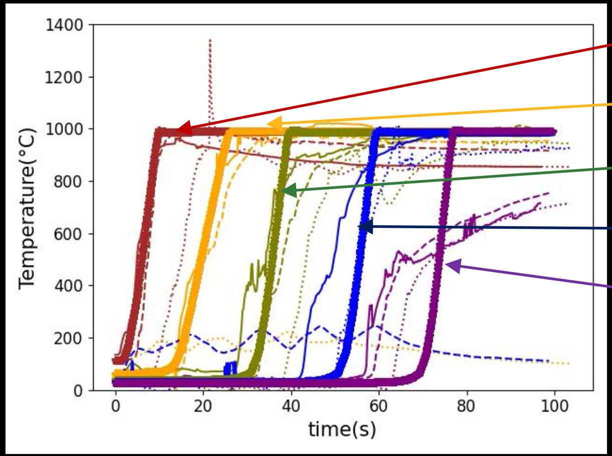


Kim et al. 2007

Thermal abuse

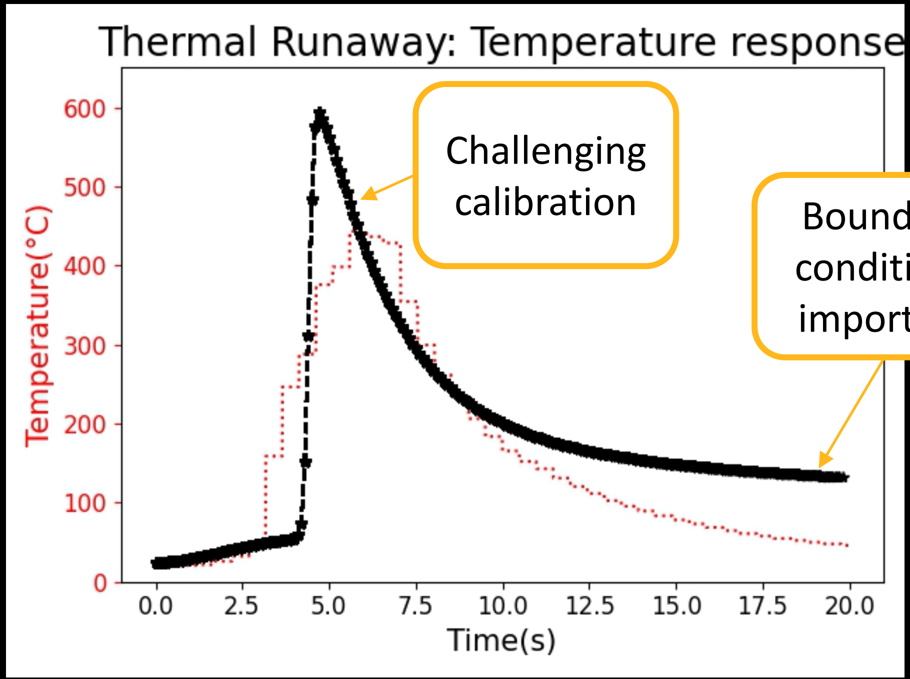
- Thermal runaway propagation





1st cell TR
2nd cell TR
3rd cell TR
4th cell TR
5th cell TR

- Thermal boundary conditions hard to capture
- Few temperature datapoints

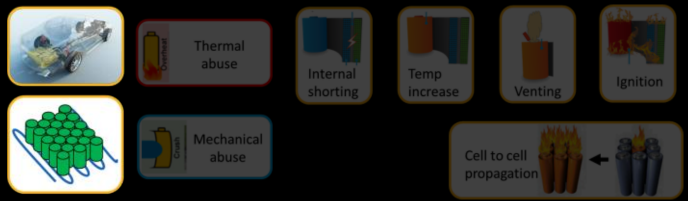


Challenging calibration

Boundary conditions important

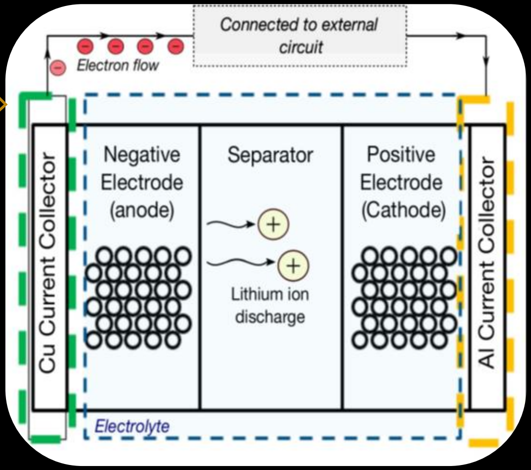
Simulation
Test

Electrical domain and battery models

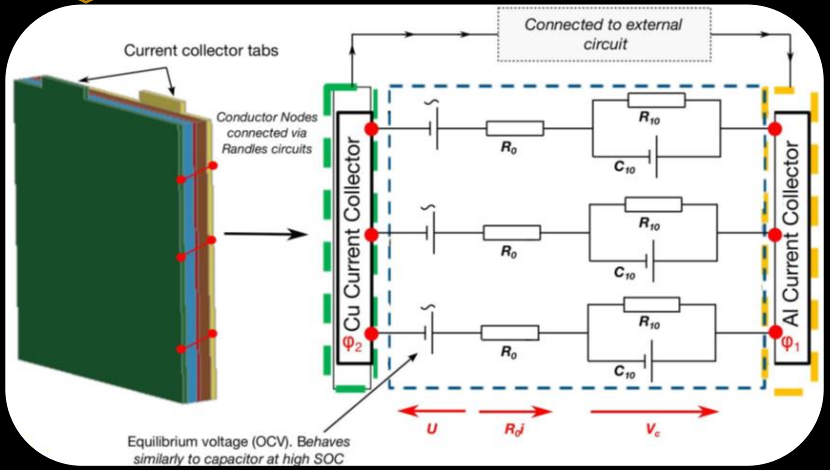


- The EM solver provides the capabilities to define
  - Electrical connections and boundary conditions
  - Battery models on micro and macro scale *EM_RANDLES_*
- Electrochemical behavior of the battery cell is represented by equivalent distributed circuit (Randles circuit)
  - Temperature and SOC dependency can be considered

Electro chemistry of a cell

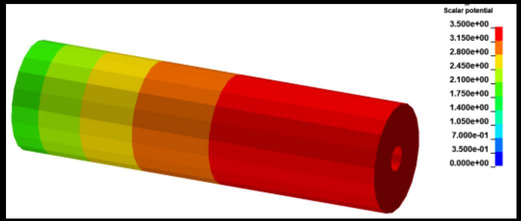


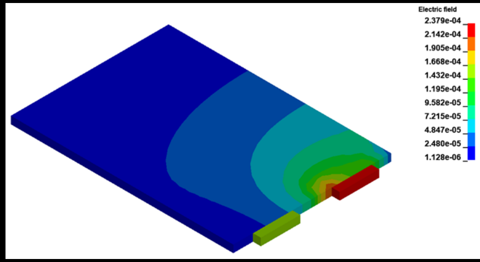
Lumped electric circuit model

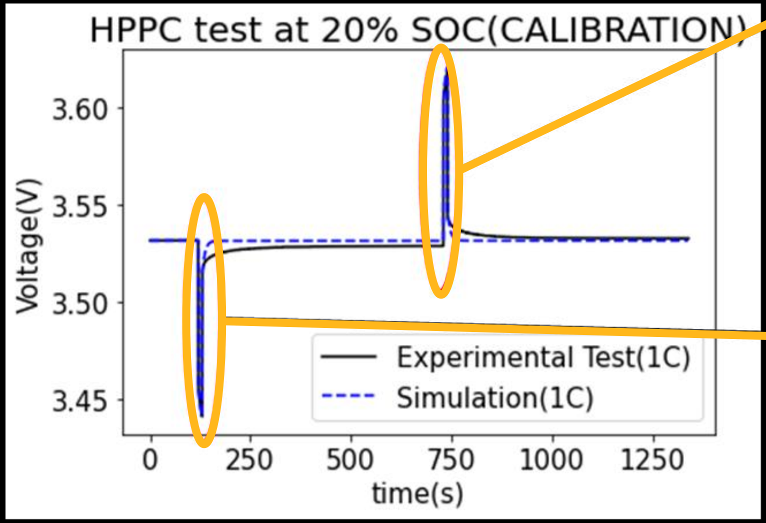


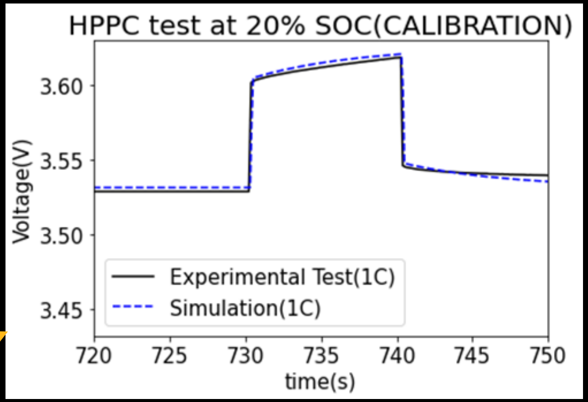
Battery tests and battery model calibration

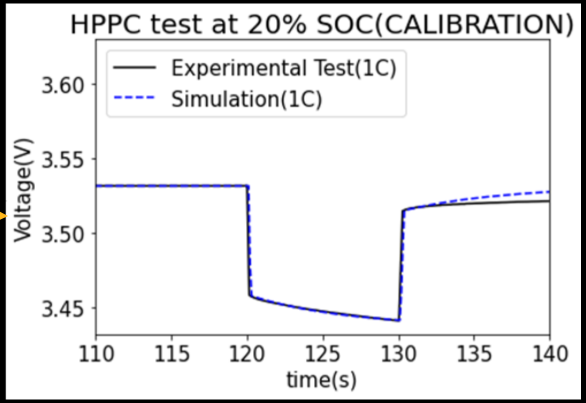
- Randles parameters are obtained from test data
- Capacity charge and discharge test (e.g. C/10 test →10h cycles)
- Hybrid pulse power characterization test (HPPC test)



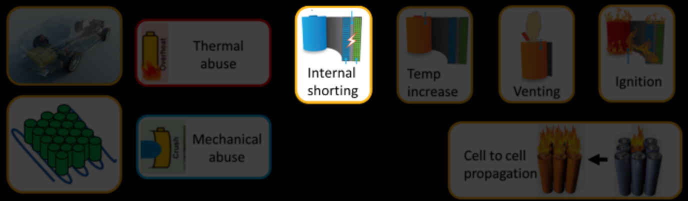




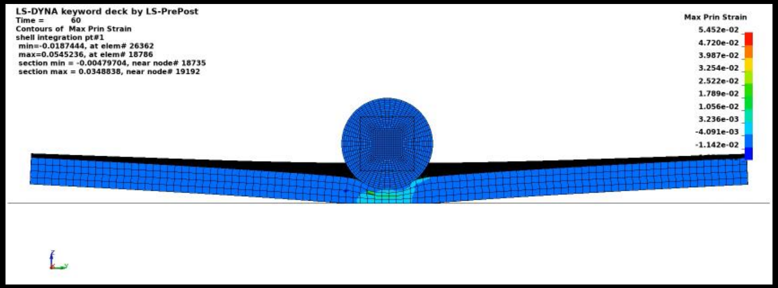


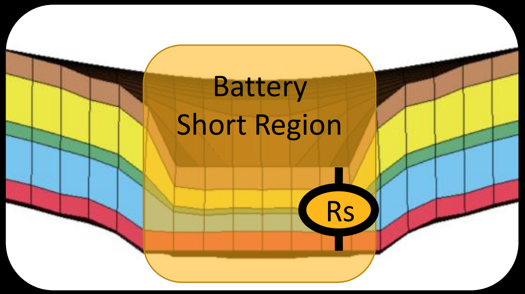


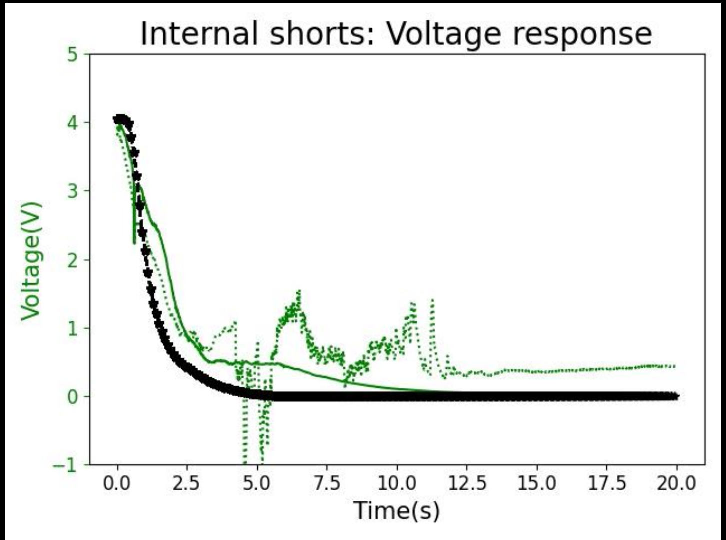
Short circuit trigger

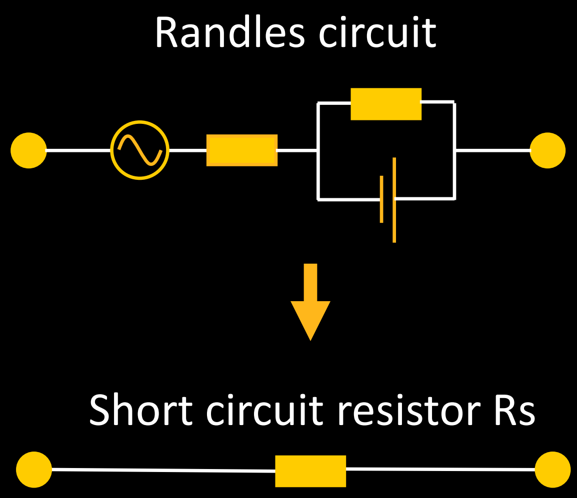


- The EM solver handles the short circuit triggered by mechanical and thermal abuse
  - Mechanical criteria
    - E.g. strains, stresses, element failure
  - Thermal criteria
    - E.g. melting temperature of separator
- In a battery short, a Randles circuit is removed and replaced by a short circuit resistance



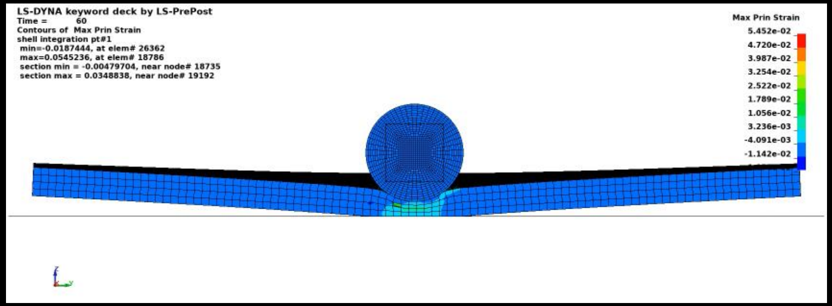


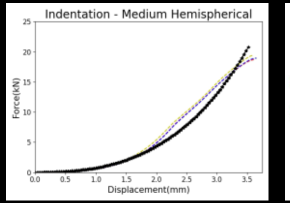


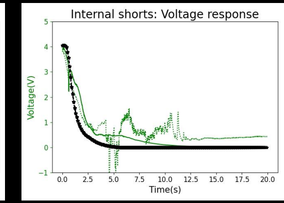


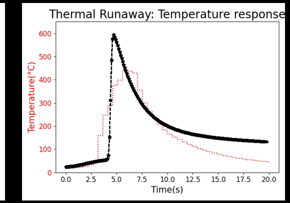
From single cell to EVs

Single cell

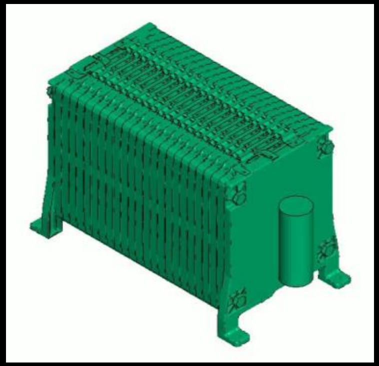


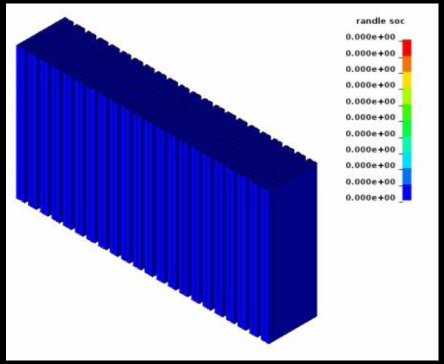






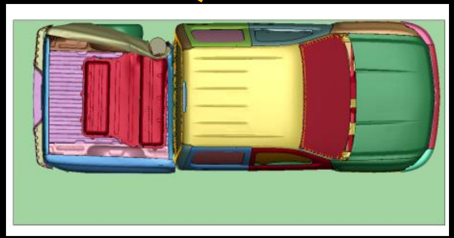
Module



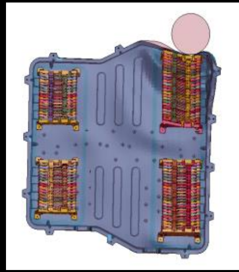


Full vehicle under crash load case

Two-Step Approach
One single simulation



Battery Deformation

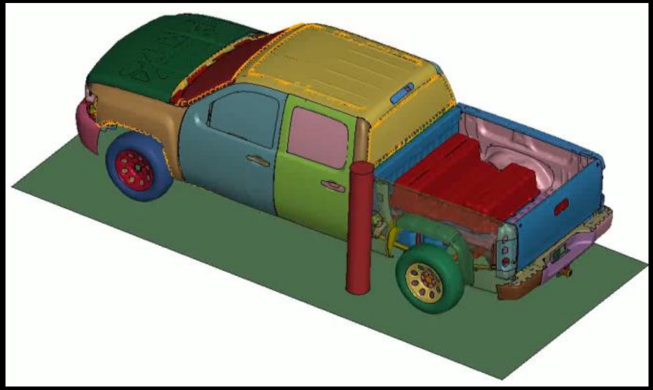


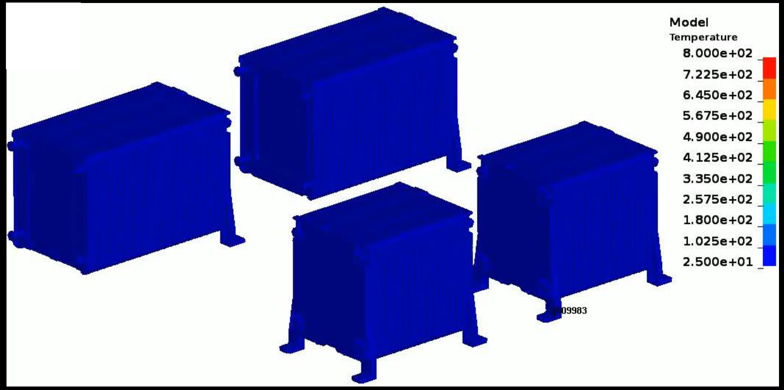
Pole Impact simulation
Small timestep

Lasts for 20 milli s

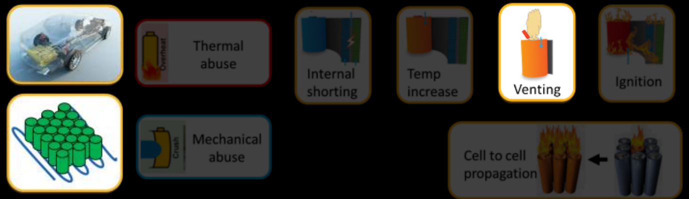
Freeze Mech Deformation (large timestep)
Compute EM & Thermal

Lasts for 10 seconds





Swelling and venting



- Swelling
  - Swelling due to SOC (normal usage)
    - SOC dependent expansions coefficient can be defined, requires EM solver
  - Swelling due to aging (long term normal usage)
    - Gas generation can not be modeled. Simplified approaches. E.g. uniform pressure profile.
  - Swelling prior venting (abuse)
    - CPM

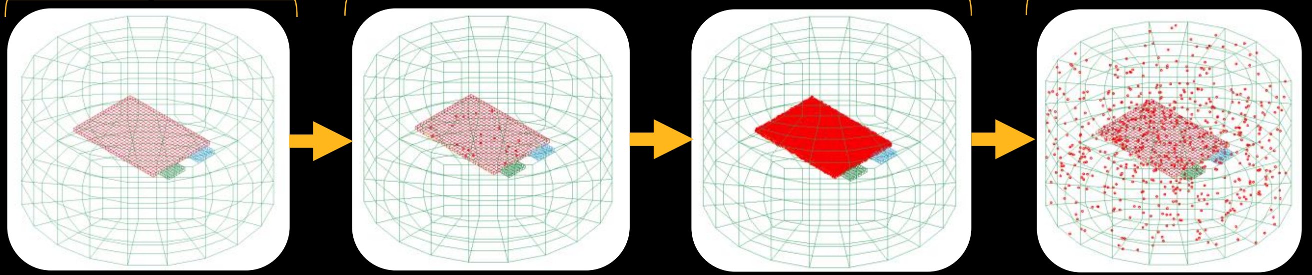
- Venting
  - Accumulated gas leads to cell burst or triggers pressure release vent
    - (CPM) results not accurate

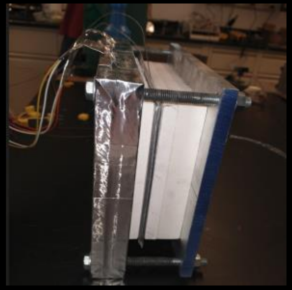
Corpuscular Particle Method (CPM) for Gas Released in Pressure Vessel

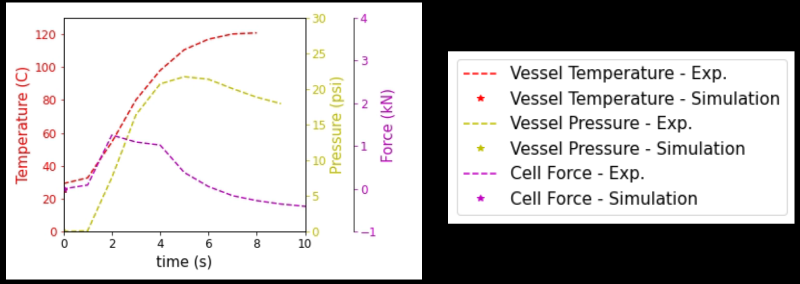
Cell in vessel, sandwiched in between rigid walls

Gas generation and accumulation within cell

Cell bursts and gas is released into vessel

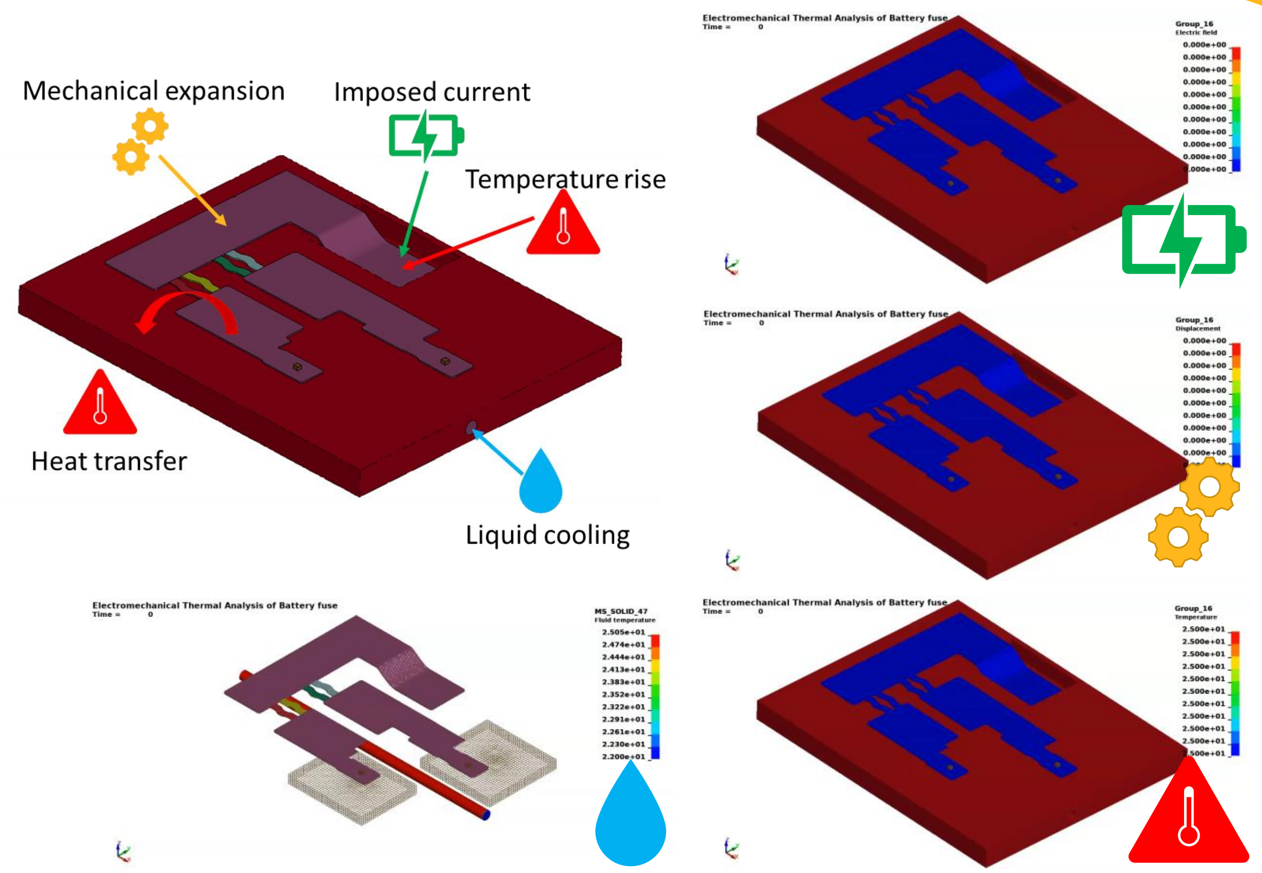




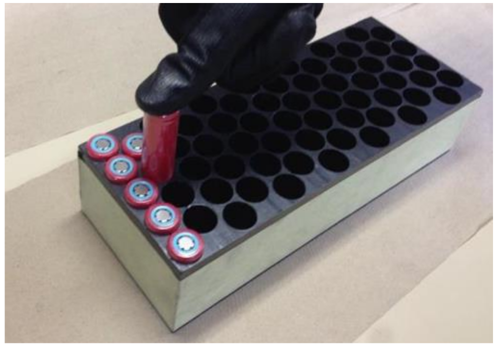


Beyond safety

Pack design – Busbar (Cell connectors)

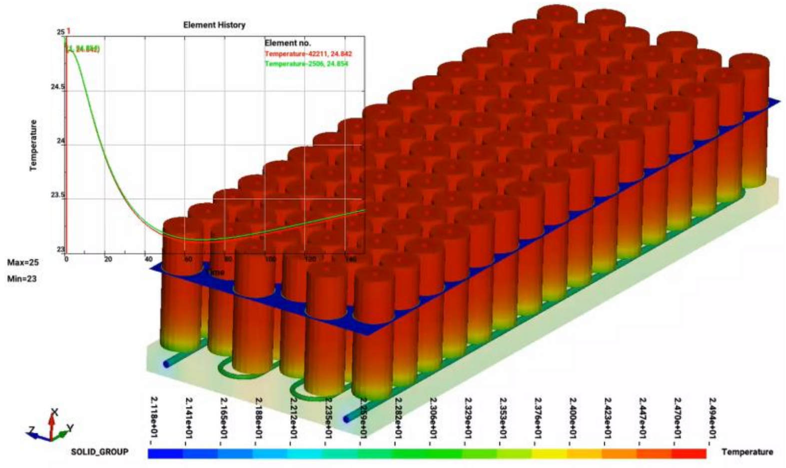


Thermal management - Cell cooling



No Cooling →
Max temp. 43°C

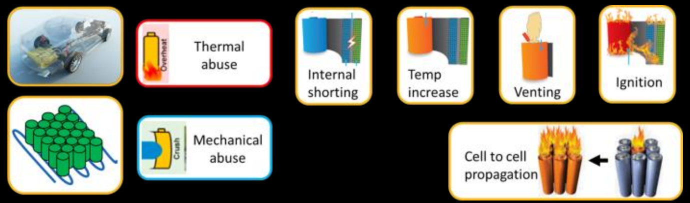
Air and liquid cooled (at 20°) →
Max temp. 23.4°C



Capabilities and challenges

Many capabilities are here

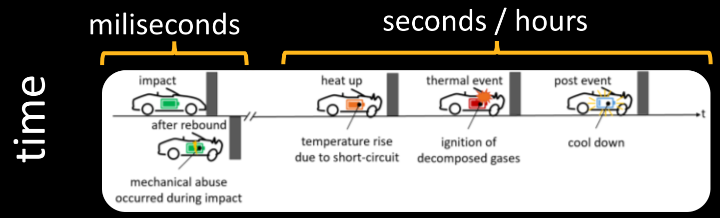
- Structural and multi physics methodologies are in place to predict short circuits on single cells and battery packs in full vehicles



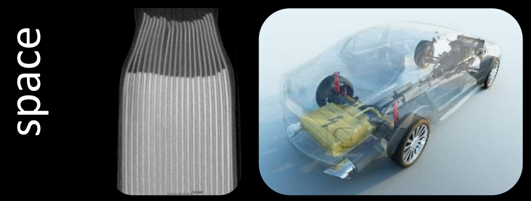
- Wide range of battery applications are possible to simulate within LS-DYNA

Still remains a challenge

- Range of scale in time



- Range of scale in space



- Big test matrix

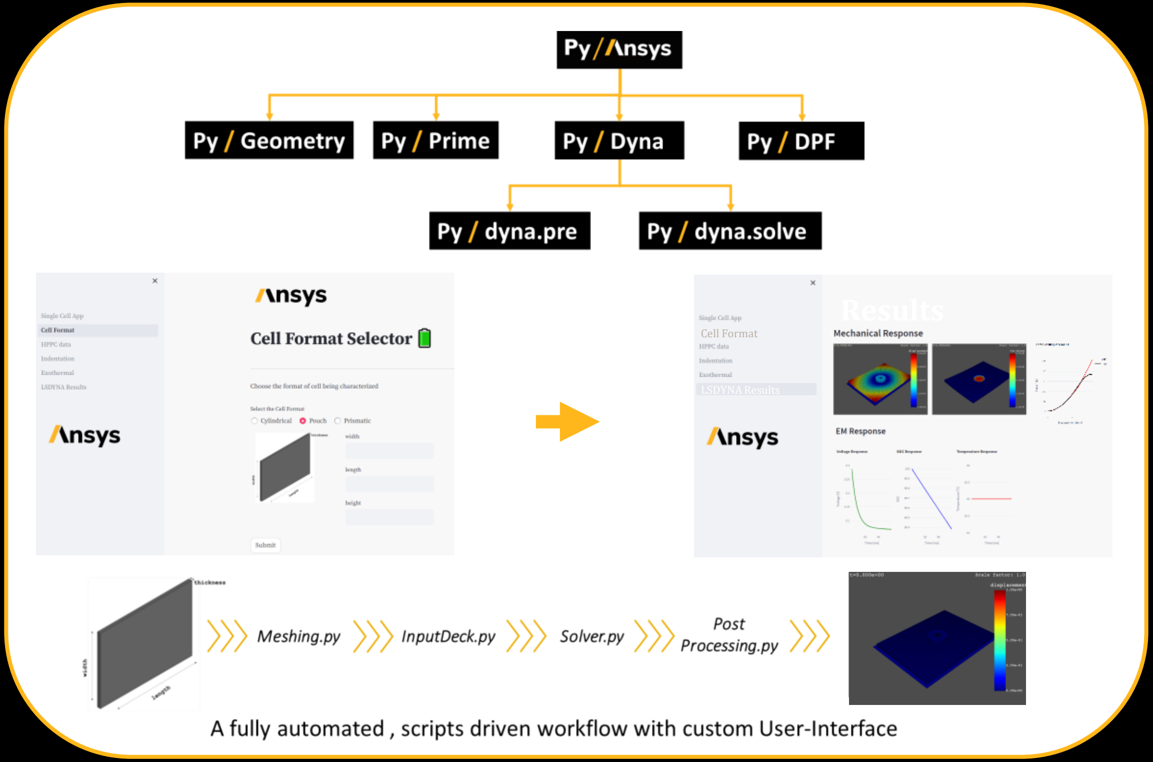
HPPC/Capacity Test
Compression, Tension, Bending, Indentation
Thermal Runaway Test

Development and one hint

- Development progresses tirelessly
  - Swelling
    - Investigate swelling without the need of the EM solver
    - Gas generation
  - Venting
    - New methodology for more accurate results in post venting scenarios
  - Electro chemistry
    - Considering detailed electro chemistry beside the lumped Randles circuit approach

- PyAnsys Automate workflows

Battery Cell Characterization Using PyDyna



Ansys

Development of LS-DYNA is customer driven.

Where are your struggles?

Your input is valuable!

Thank you!

Ansys