EV Battery Modelling Concepts Using Ansys LS-DYNA

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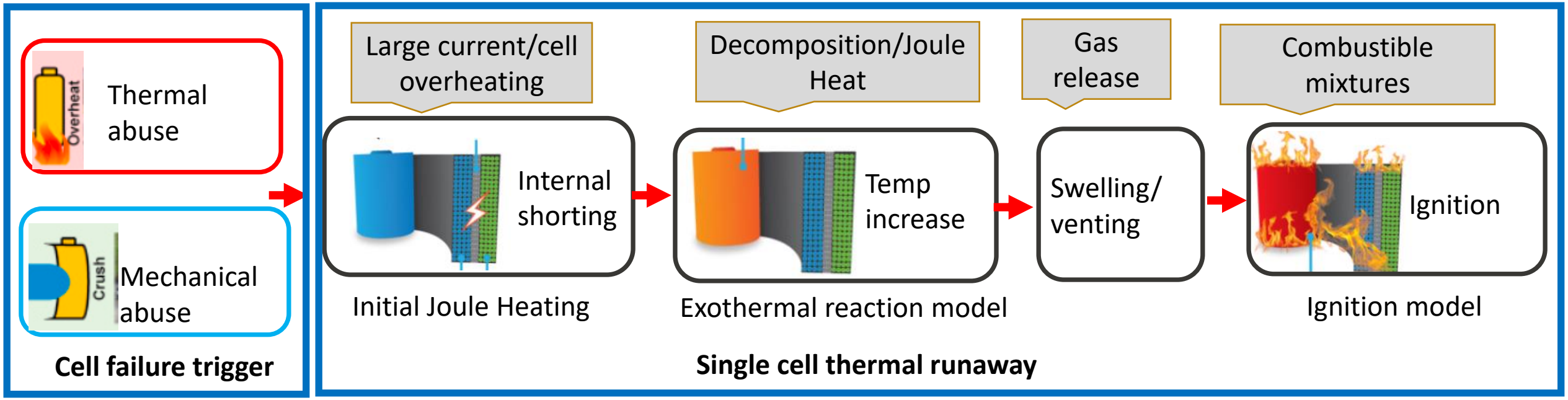
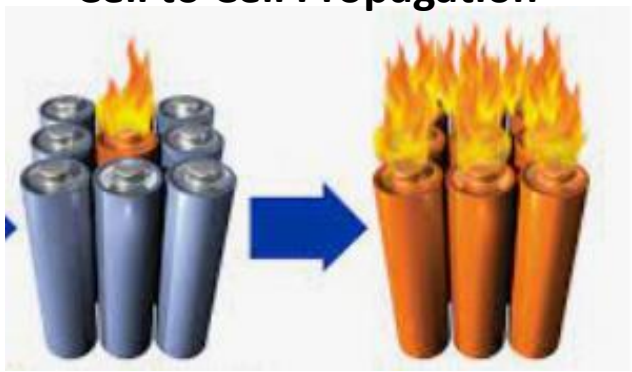
Vehicle Safety

- Safety key focus of EVs
- Fire is rare but could be very dangerous
- We still lack full understanding of battery behavior under abuse
- In a crash
  - What caused the short ?
  - Will the battery explode? Will it catch fire in a few minutes or hours?
- Needs strong Multi-Physics capabilities to predict this behavior

Battery Safety Workflow



Cell to Cell Propagation



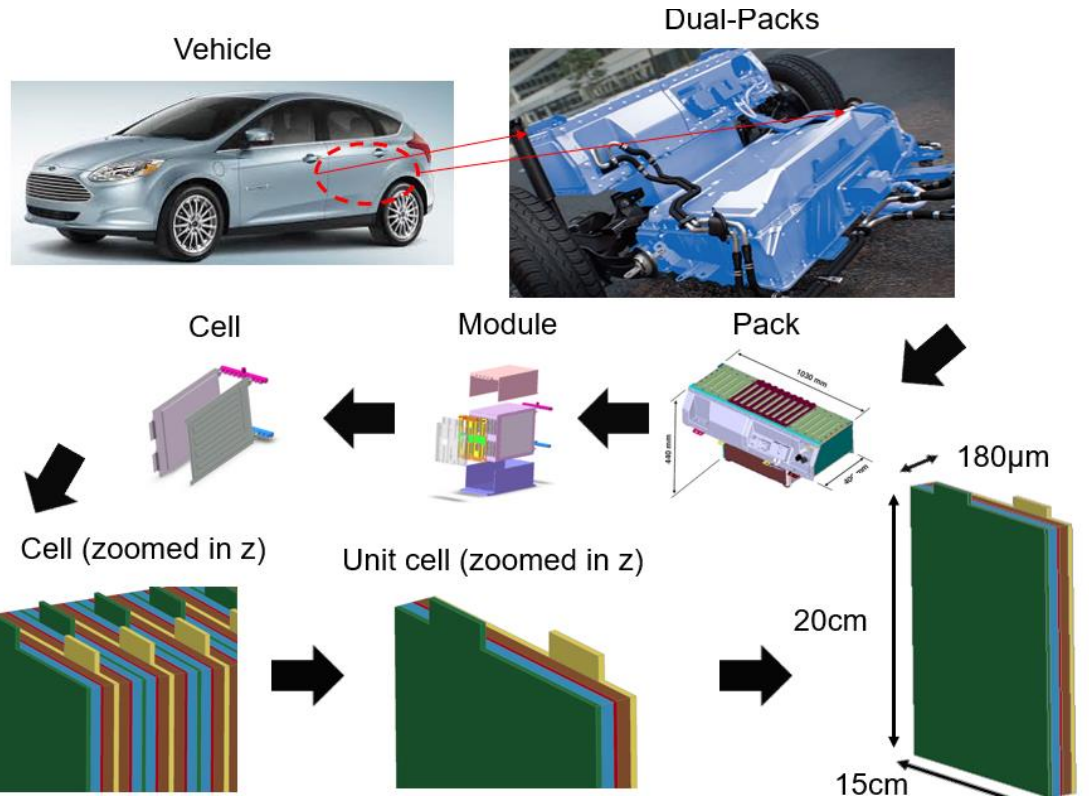
Thermal contact

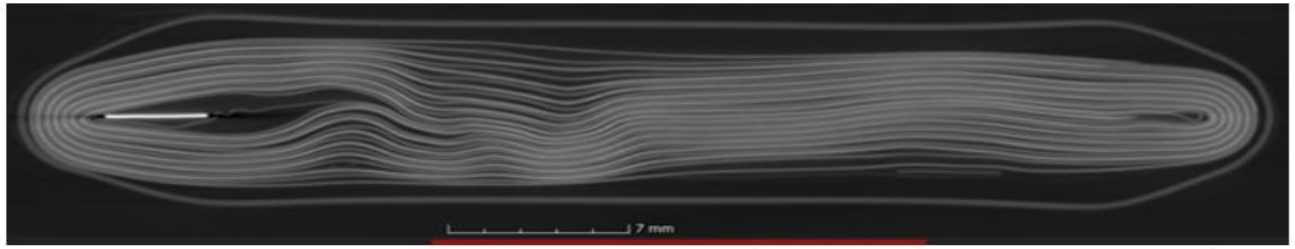
Computational challenges

- **Complex multiphysics**:
  - Mechanical
  - Electromagnetics
  - Electrochemistry
  - Thermal

- **Wide range of length scales**: battery size around 1m while individual layers in a cell have thicknesses around 0.01~0.1mm: and it is at the level that the internal shorts trigger the thermal runaway

- **Wide range of time scales:** from crash in ms to thermal runaway, fire and explosion than can take mn to hours and even days





CT scan of battery from deep discharge swelling (Image Courtesy of DfR Solutions)

Background

These developments in LS-DYNA started in 2015 as a **collaboration between LSTC and Ford Motor Company**, Research and Innovation Center

Overall project objective: Develop a practical simulation tool to predict the combined structural, electrical, electrochemical, and thermal (EET) responses of automotive batteries to crash-induced crush and short circuit, overcharge, and thermal ramp, and validate it for conditions relevant to automotive crash.

Funding: DOE EERE VTO, Jan 2016 – Dec 2018

A6440 *Journal of The Electrochemical Society*, **164** (1) A6440-A6448 (2017)

FOCUS ISSUE OF SELECTED PAPERS FROM IMLB 2016 WITH INVITED PAPERS CELEBRATING 25 YEARS OF LITHIUM ION BATTERIES

A Simulation Framework for Battery Cell Impact Safety Modeling Using LS-DYNA

James Marcicki,[a,z] Min Zhu,[a] Alexander Bartlett,[a] Xiao Guang Yang,[a] Yijung Chen,[a] Theodore Miller,[a] Pierre L'Eplattenier,[b] and Iñaki Caldichoury[b]

[a]*Ford Motor Company, Research and Innovation Center, Dearborn, Michigan 48124, USA*
[b]*Livermore Software Technology Corporation, Livermore, California 94551, USA*

Journal of The Electrochemical Society, **166** (14) A3119-A3121 (2019)
0013-4651/2019/166(14)/A3119/3/$38.00 © The Electrochemical Society

Communication—Multi-Physics battery Safety Simulations acr Length Scales

Jie Deng,[1,z] Chulheung Bae,[1] Theodore Miller,[1] Pierre L'Eplattenier,[2] and Inaki Caldichoury[2]

[1]*Ford Motor Company, Dearborn, Michigan 48124, USA*
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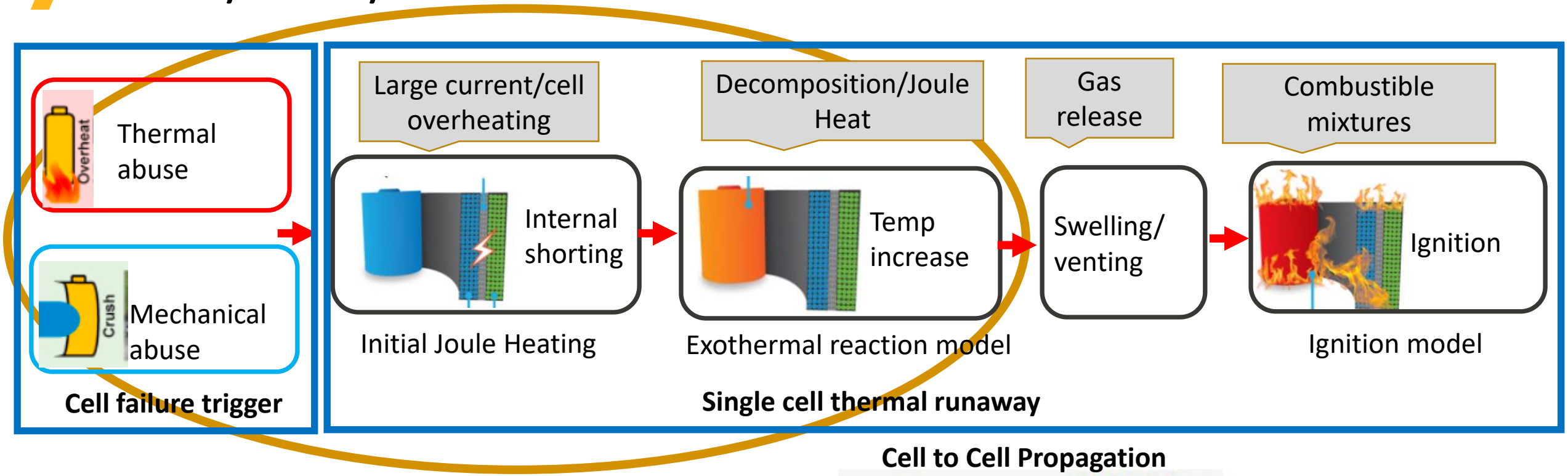
Journal of The Electrochemical Society, 2020 **167** 090550

Impact Modeling and Testing of Pouch and Prismatic Cells

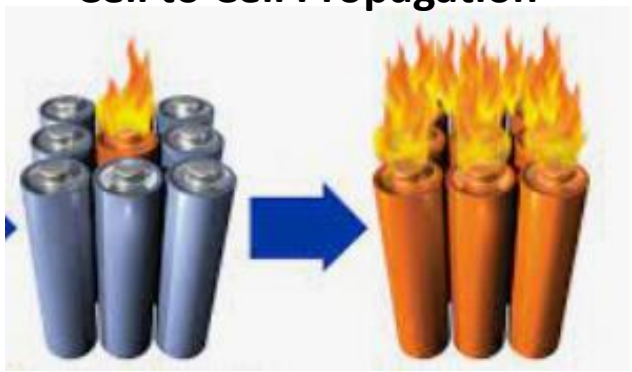
Jie Deng,[1,z] Ian Smith,[2] Chulheung Bae,[1] Phil Rairigh,[1] Theodore Miller,[1] Bapiraju Surampudi,[2] Pierre L'Eplattenier,[3] and Inaki Caldichoury[3]

[1]*Ford Motor Company, Dearborn, Michigan 48124, United States of America*
[2]*Southwest Research Institute, San Antonio, Texas 78238, United States of America*
[3]*Livermore Software Technology, Livermore, California 94551, United States of America*

Battery Safety Workflow

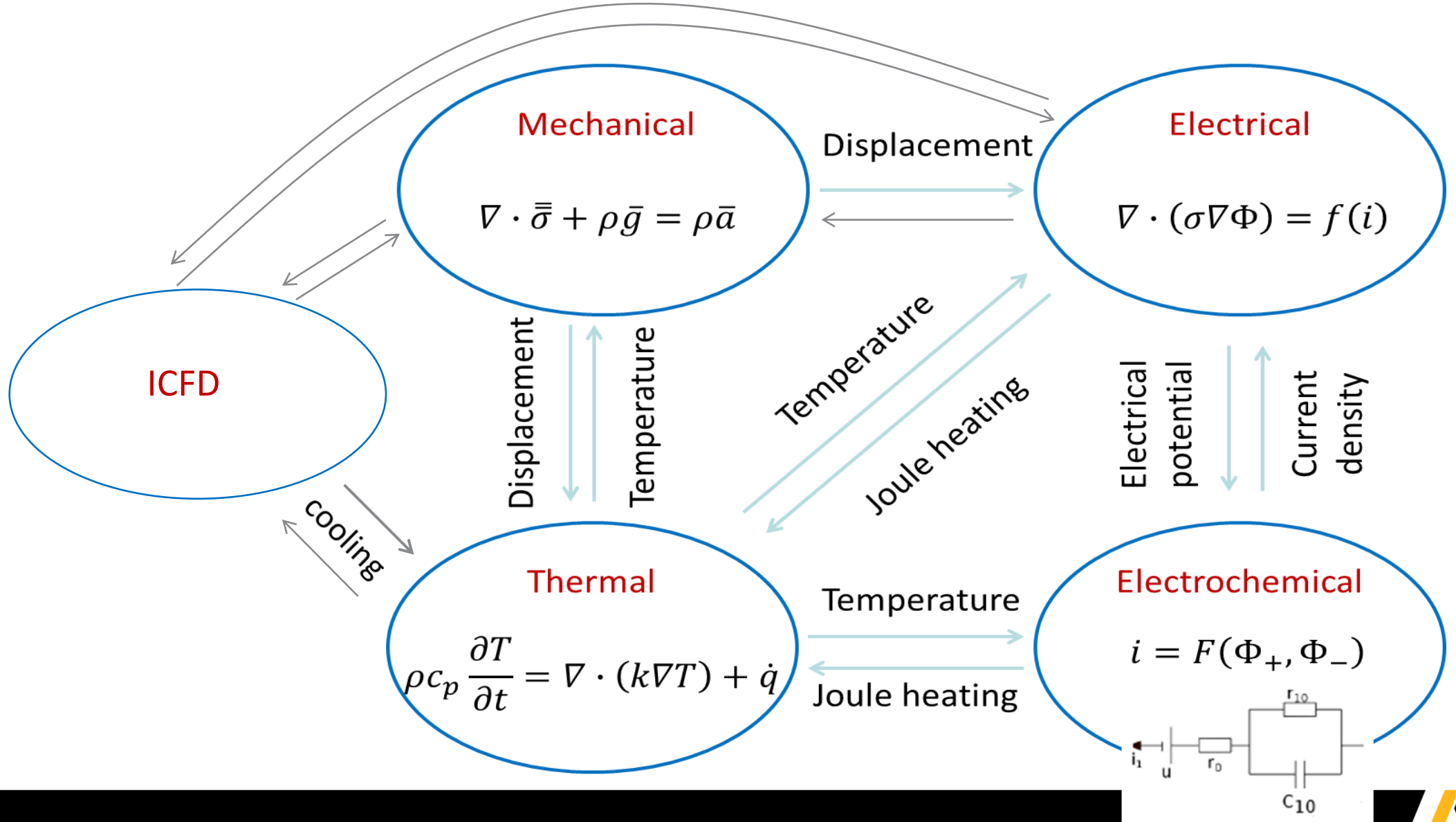


Cell to Cell Propagation



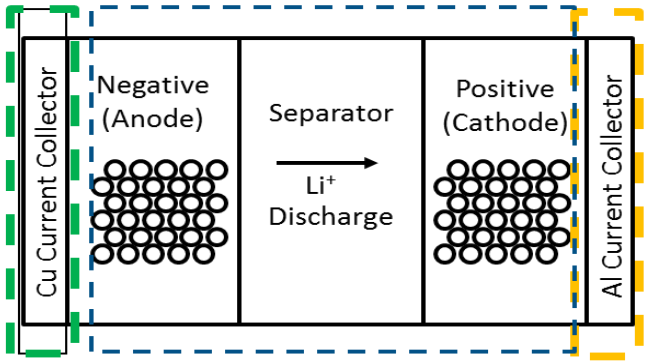
Thermal contact

Automatic coupling between LS-DYNA solvers

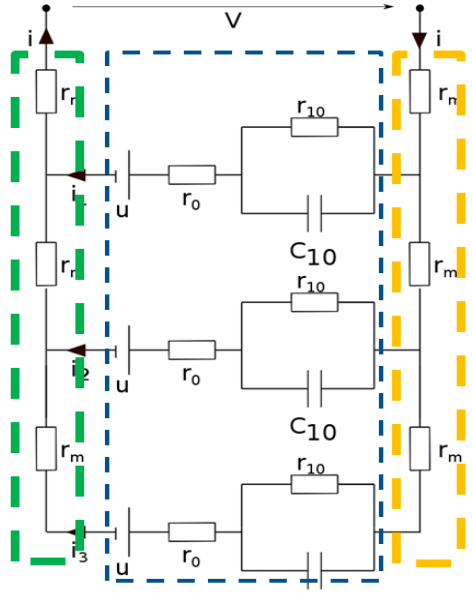


All the models are based on equivalent circuits

Electro-chemistry in the electrodes simulated by equivalent distributed electrical circuits (Randles circuits).

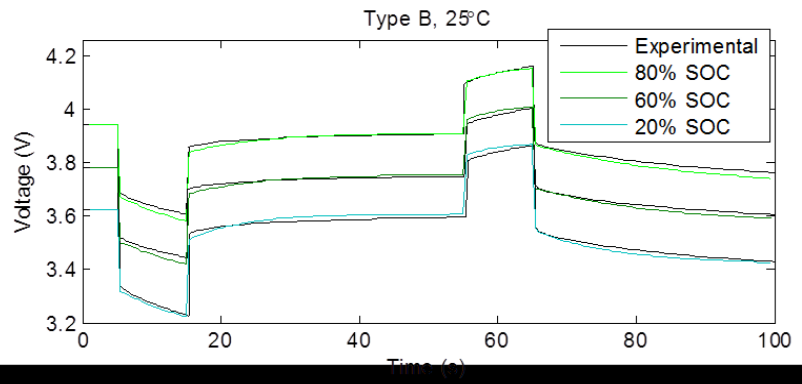


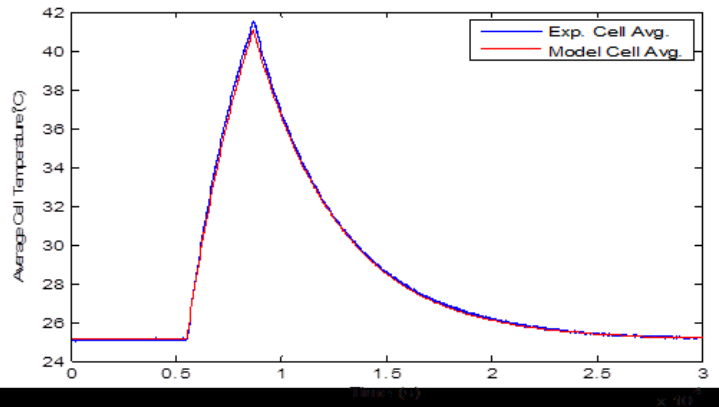
- Current collectors transport electrons to/from tabs; modeled

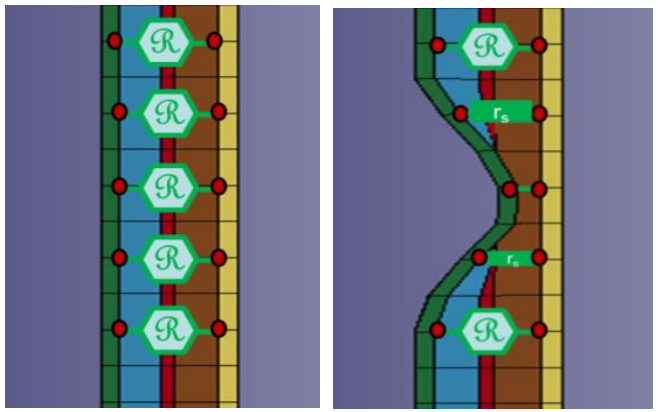


Advantages of distributed circuit model

- Not too expensive computationally
- Accurately reproduces main features of a cell (electrical, thermal)
- Easy to get the cell parameters from voltage/current measurements
- Simple to electrically connect to external circuits (connectors, buses, …) and to model external shorts
- Ability to model internal short
- Other models will be added

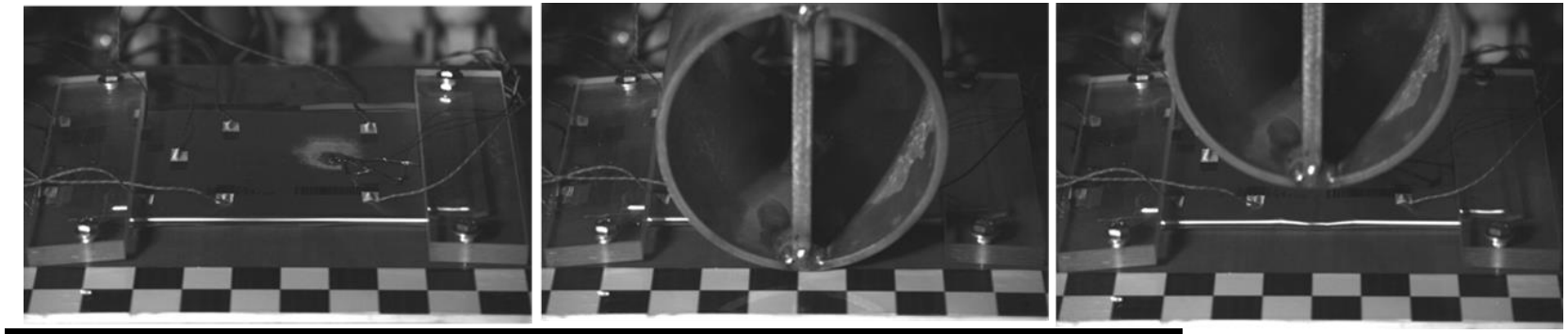






Dealing with the different time scales

- Do mechanics+EM+thermal with usual crash time steps during ~ms crash time.
- Get the deformations and shorts.
- Continue the run by “freezing” the mechanics, and do only EM+thermal with ~s time steps to let the battery discharge through the shorts and get the temperature increase (for mn or hours if needed).
- For these simulations, the EM and thermal solvers are not too sensitive to the time step apart from getting correct discretization of battery discharge and temperature increase.



[redacted]

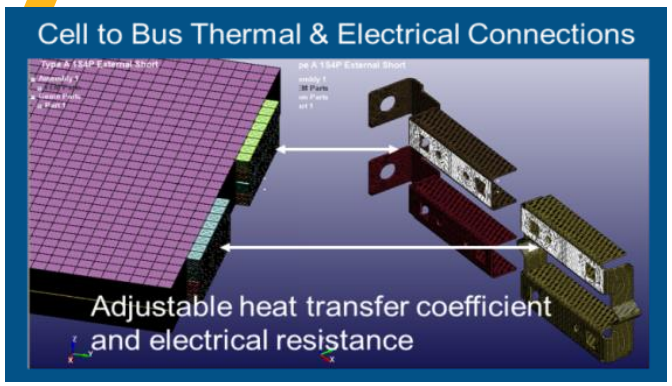
Mech + Electrical + Thermal
tf = 50 µs
dt = 0.2 µs

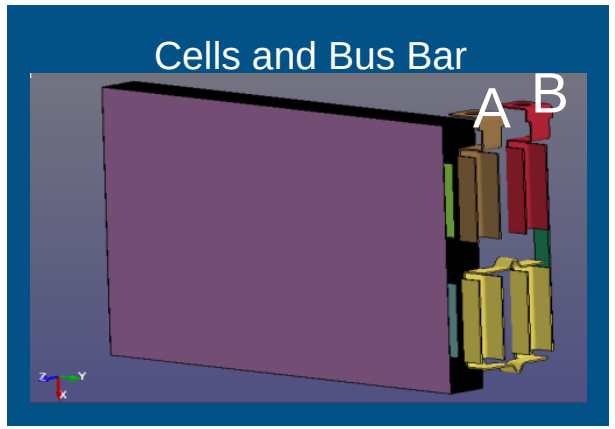
“Freeze” mechanics

Electrical + Thermal
tf = 50 s
dt = 1 s

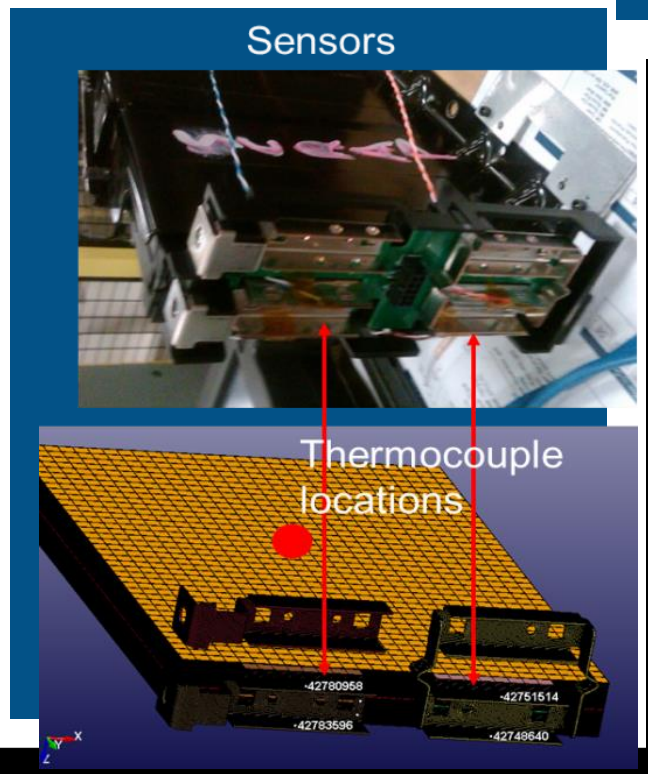
Courtesy of Ford Motor Company

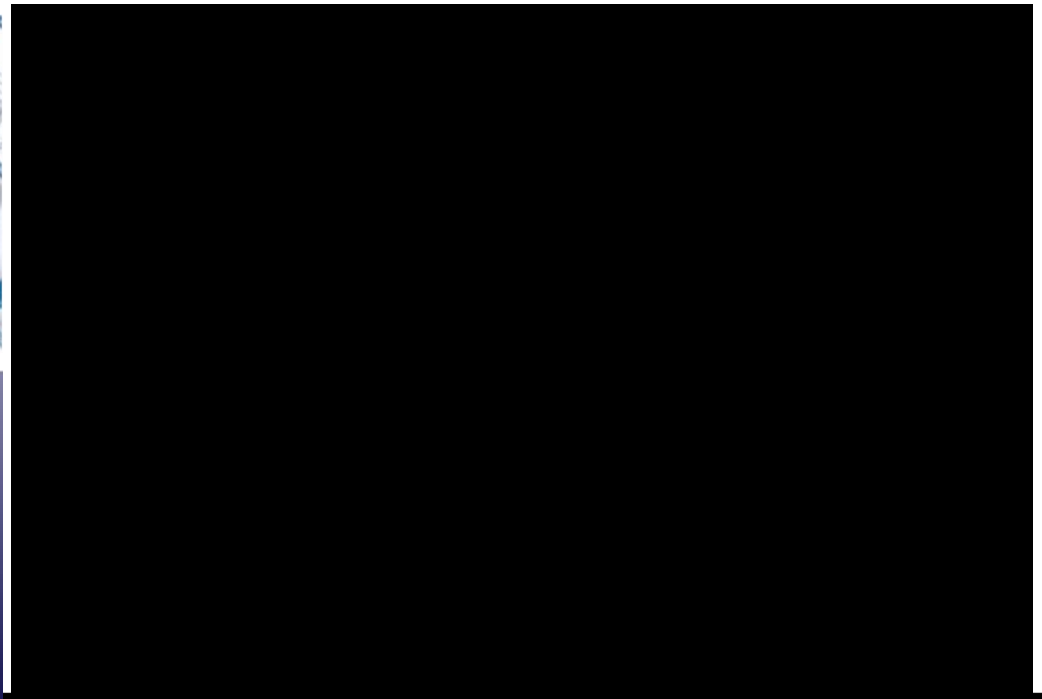
Example – solid elements – external short



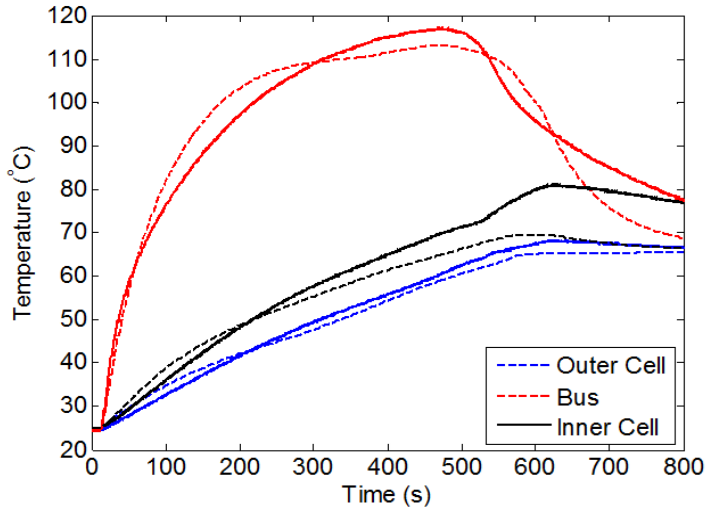


Short circuit resistance applied between A and B creates current pathway





Model Predicted (Dashed) Temperatures versus Experiment (Solid)

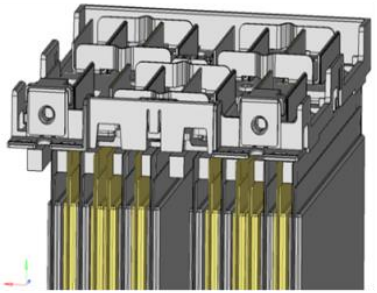


Courtesy of Ford Motor Company

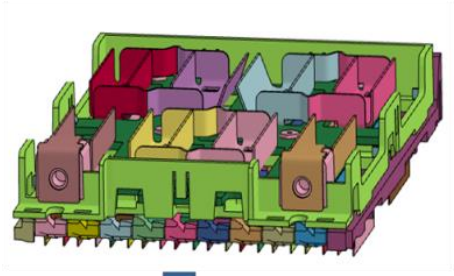
Example – meshless – external short

Crush of the bus connectors in a 5p4s module

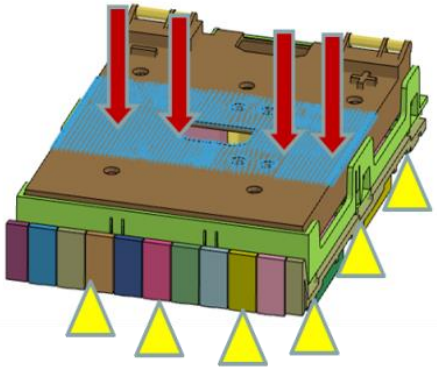
5p4s module



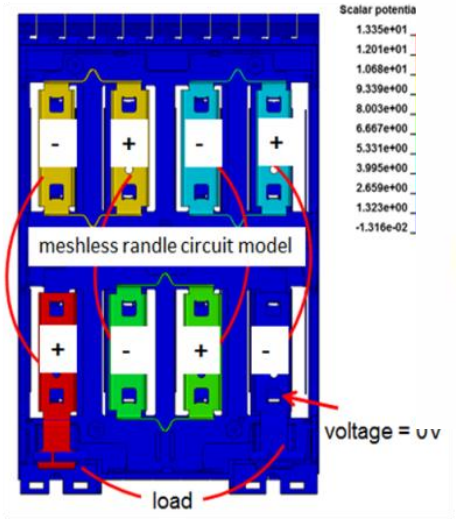
Meshless randle circuit model



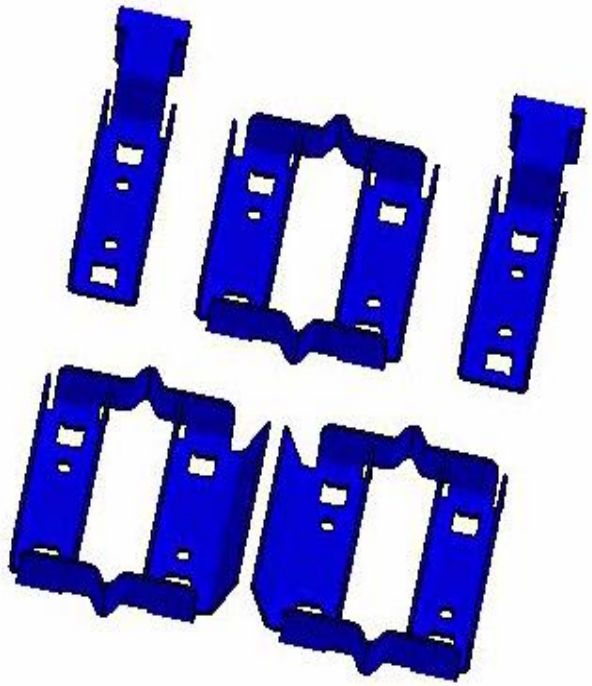
nodal prescribed motion



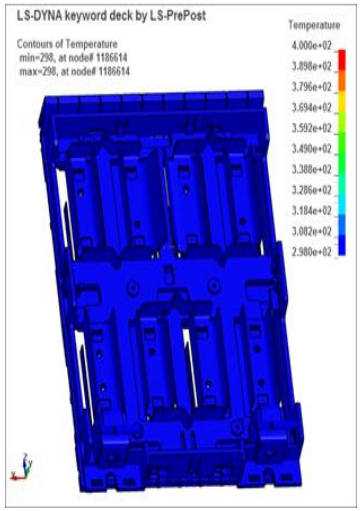
Fixed BC

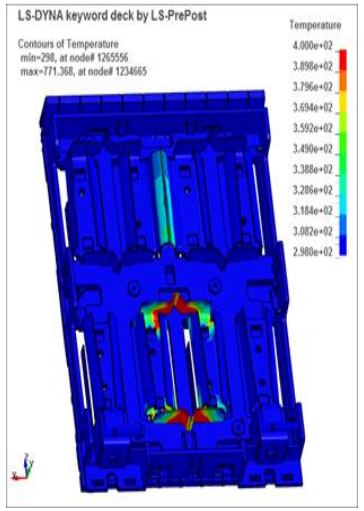


Potential



Temperature



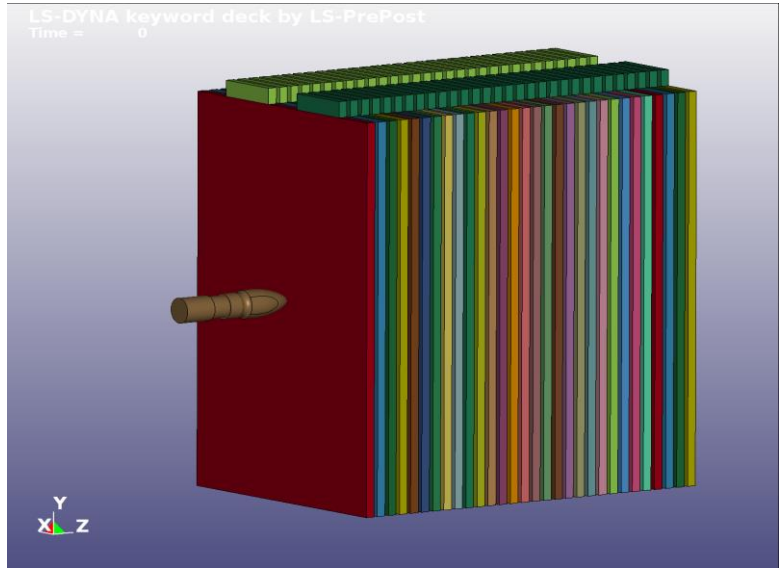


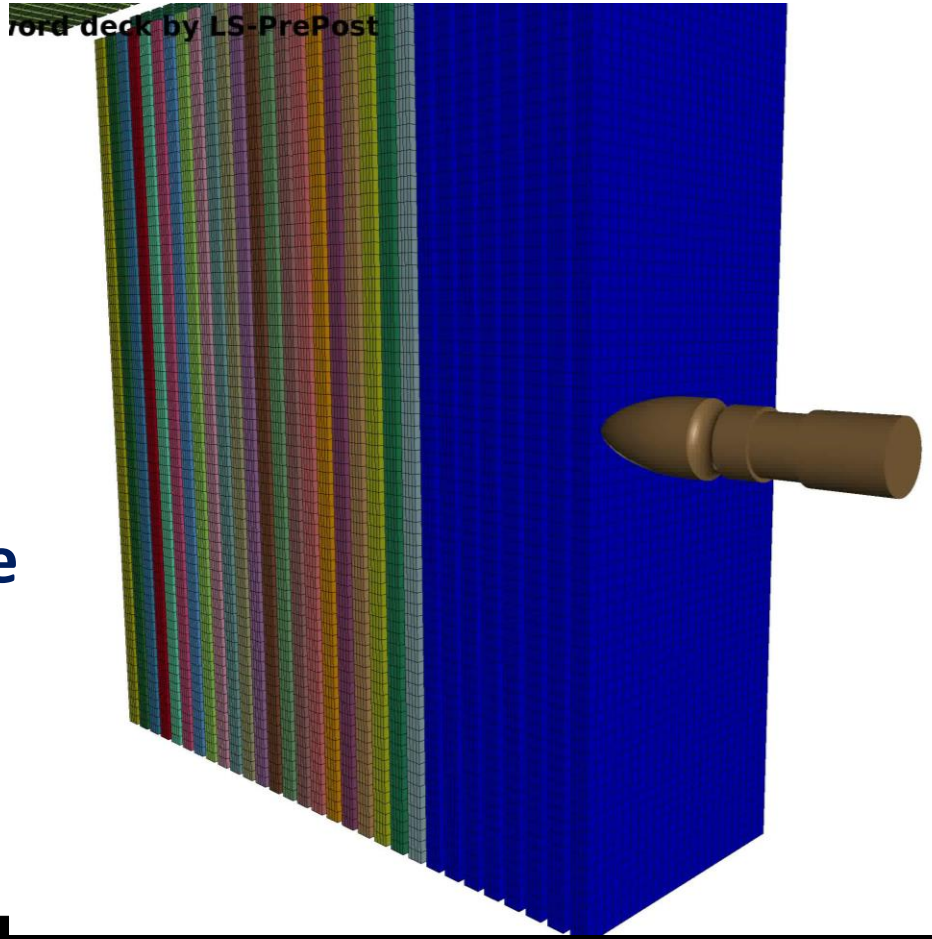
Courtesy of Ford Motor Company

Nail penetration (Batmac)

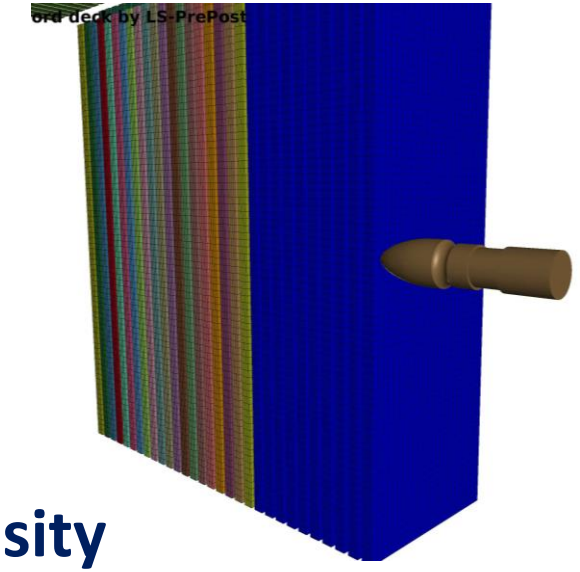
Nail penetrating a 30 cells pack creating holes (erosion), short circuits and temperature elevation

Batmac for the first 10 cells, meshless for the rest



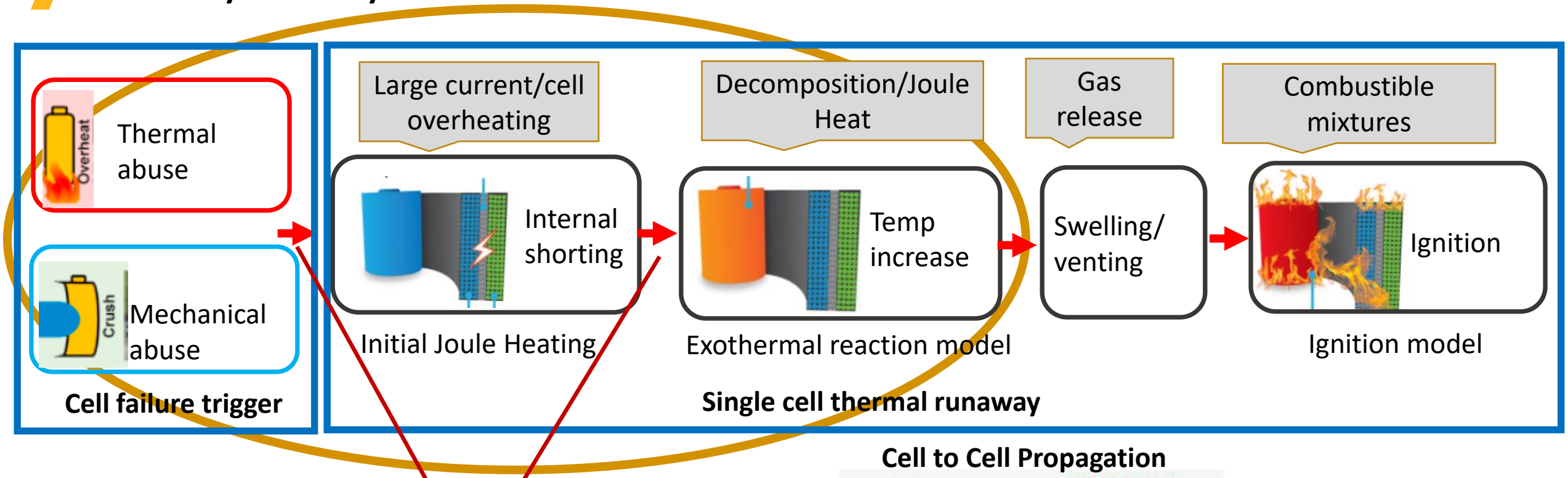


Temperature



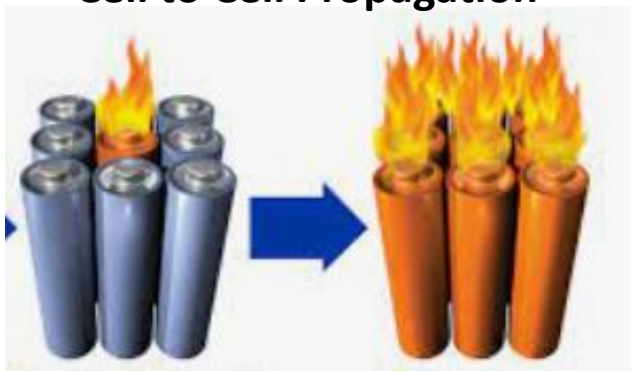
Current density

Battery Safety Workflow



User defined transitions

Cell to Cell Propagation

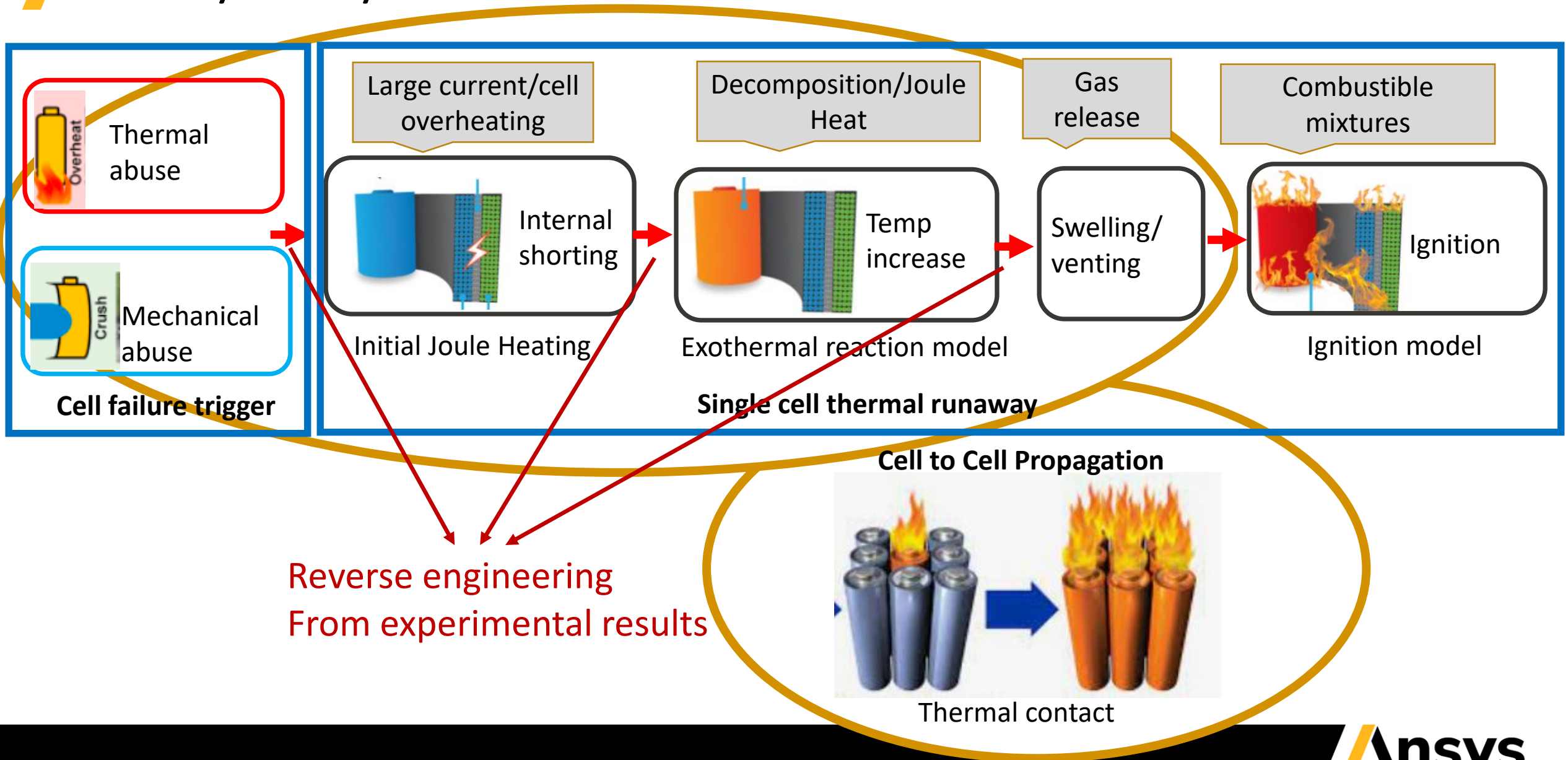


Thermal contact

Ansys battery abuse program

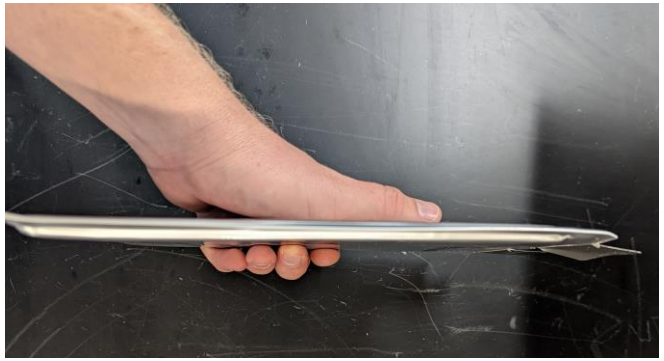
- Solvers themselves rely on experimental tests to characterize some of their equations
  - Cell mechanical and thermal properties
  - Onset of internal short in function of local mechanical and thermal fields (abuse)
  - Value of short resistance in function of these fields
  - Gas emission as a function of temperature
  - …
- These relations are highly cell dependent (cell geometry, chemistry, …)
- Ansys is implementing a workflow from single cell experiments to obtaining the numerical parameters needed for a full electric vehicle crash modeling.
- The sequence of steps can be repeated for other electric or hybrid vehicles with different battery cells.

Battery Safety Workflow



Cell Information

- An automotive grade pouch battery cell is used for testing and simulation.

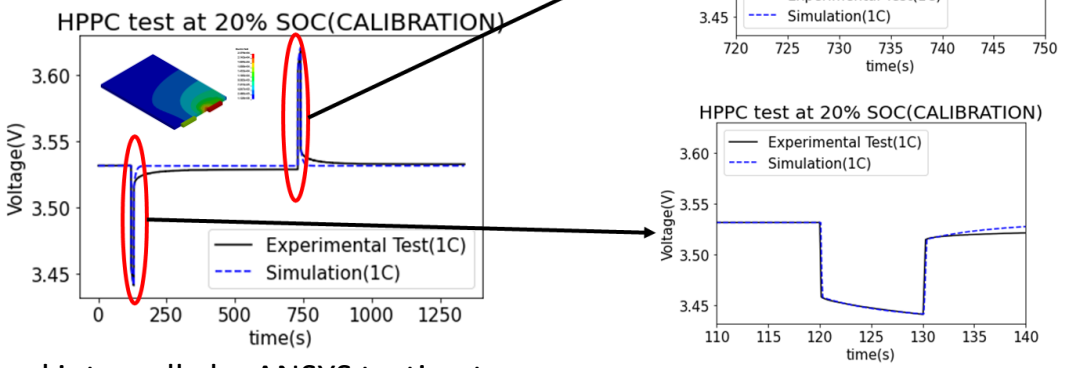


- All cells are tested in 100% state of charge (SOC) level.

Cell Electro-Chemical Characterization

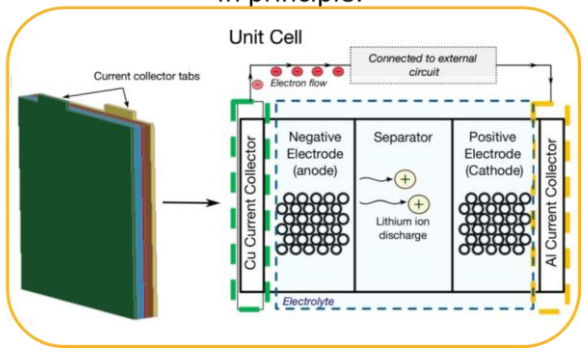
- Electro-Chemistry of the cell is represented by equivalent distributed circuit (Randles Circuits).
- Randles parameters (as a function of SOC level and temperature) for cell model input are obtained from HPPC/capacity test*.
- For the HPPC test, cell is rapidly charged/discharged and slowly discharged to next SOC level. This test profile captures cell's dynamic and static electrical properties.

Randles parameters are verified in HPPC simulation

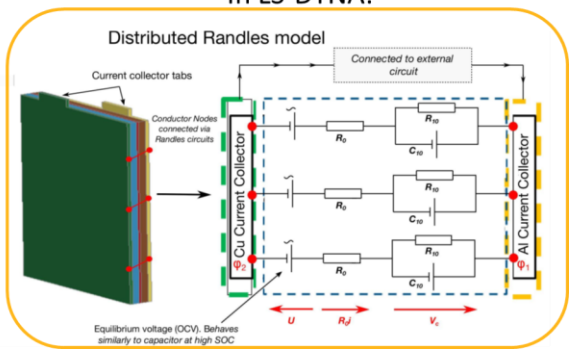


*Performed internally by ANSYS testing team

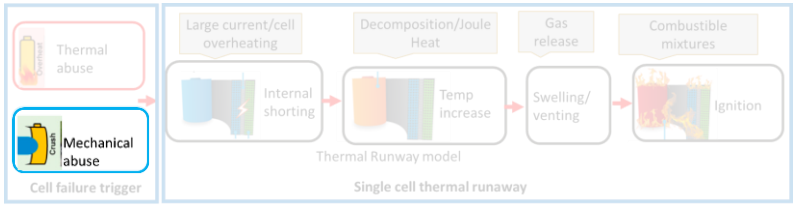
In principle:



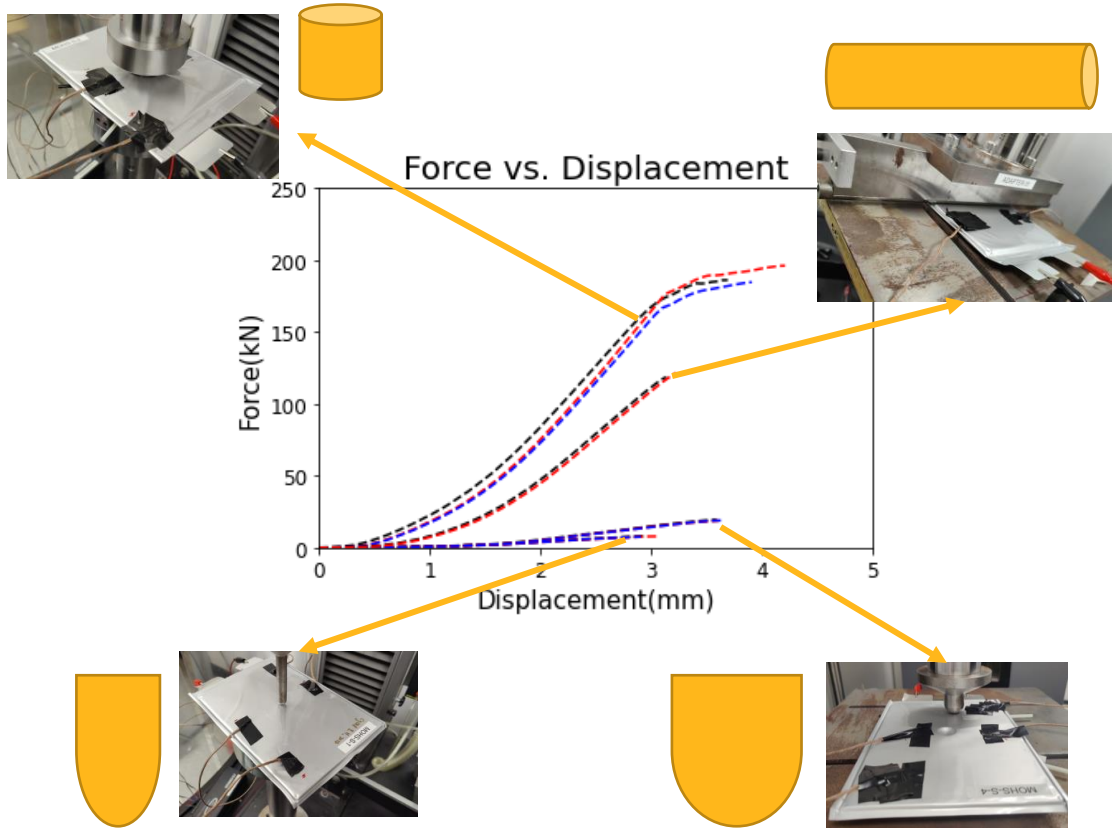
In LS-DYNA:



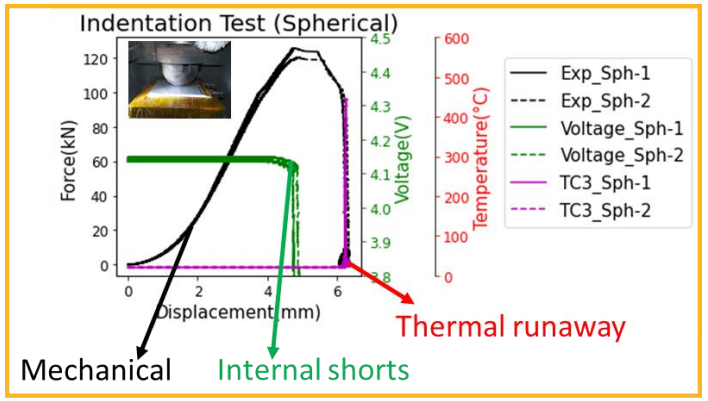
Cell Mechanical Abuse - Experimental Test

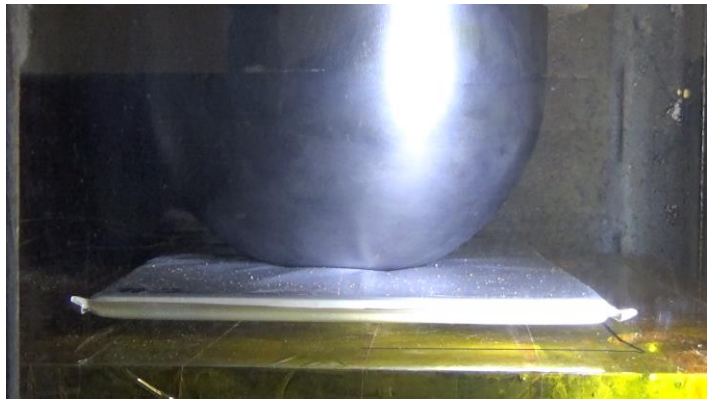


Various mechanical tests were conducted to calibrate and validate cell's mechanical properties.

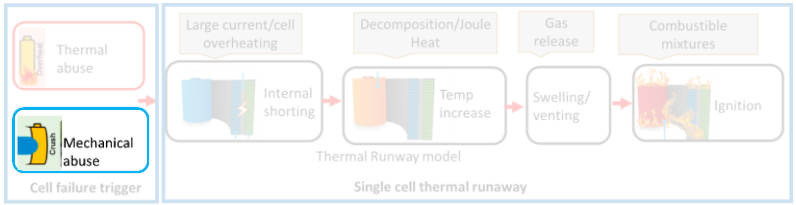


Voltage and temperature were measured during internal shorts and thermal runaway event due to mechanical loading.

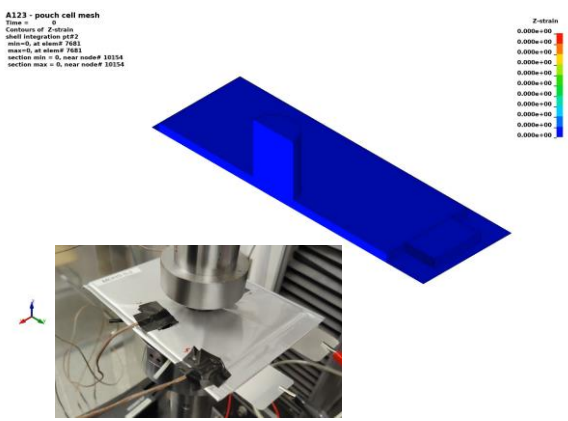


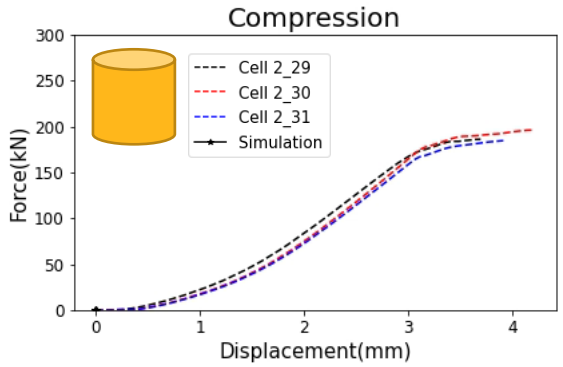


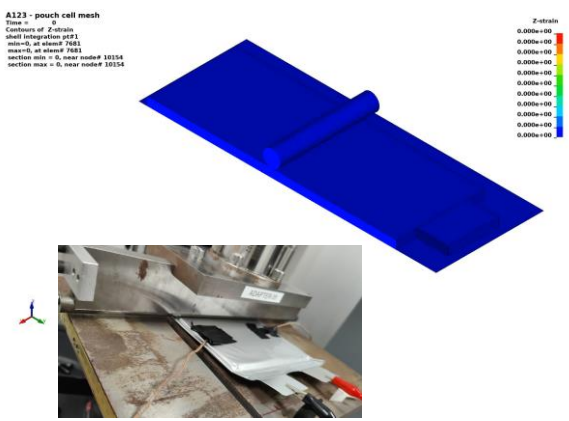
Cell Mechanical Abuse - Simulation Results

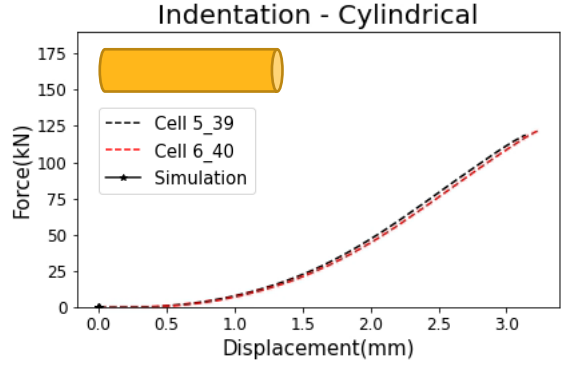


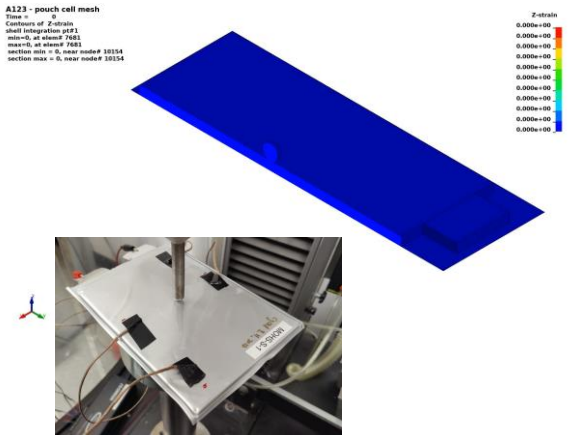
Crushable foam (*MAT_063) material model in LS-DYNA is used to simulate cell's mechanical properties.
In search of common failure criteria across various loading conditions.

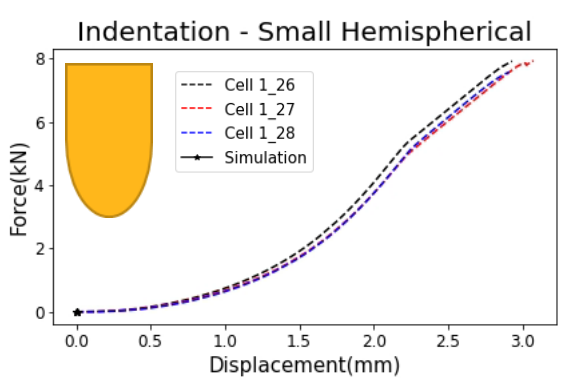


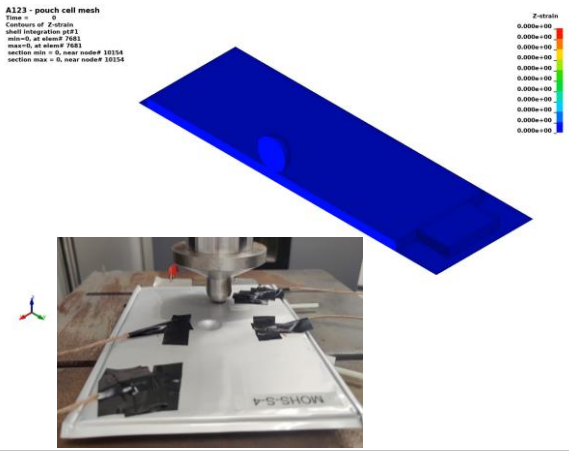


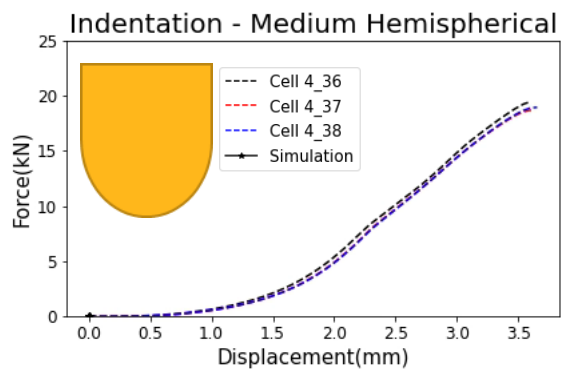




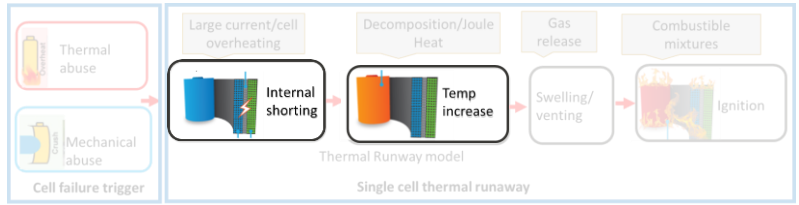




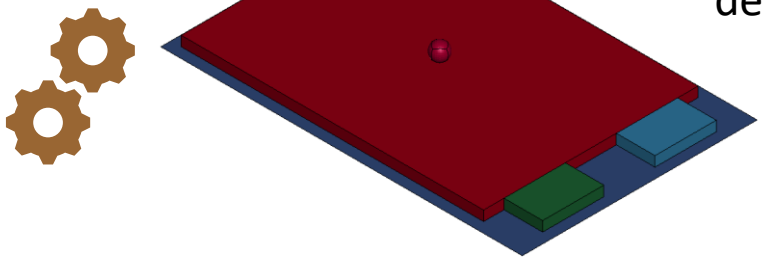




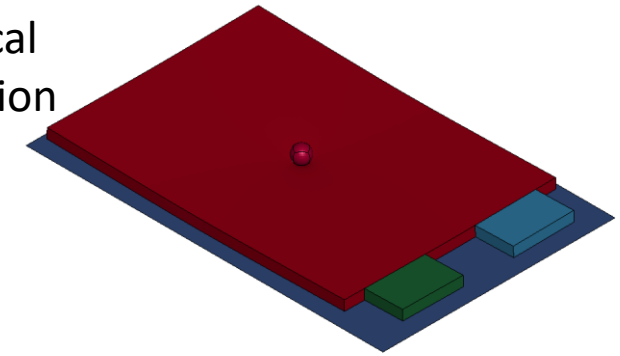
Cell Mechanical Abuse - Simulation Results

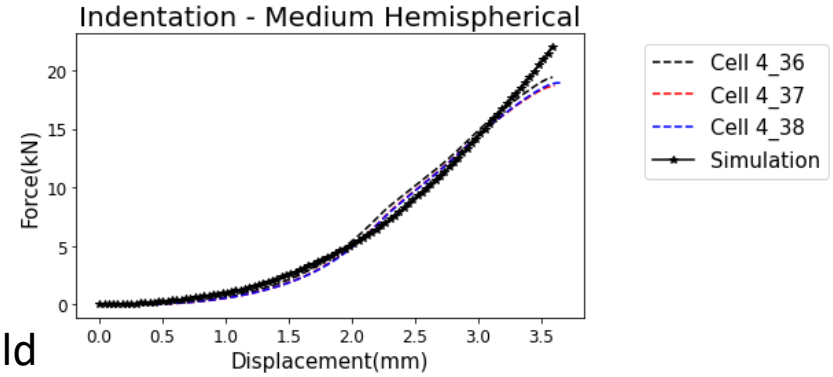


Structures



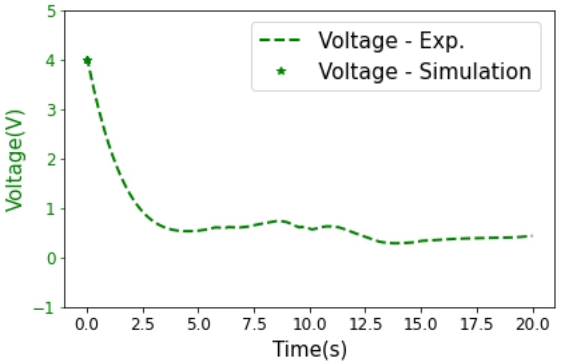
Mechanical deformation

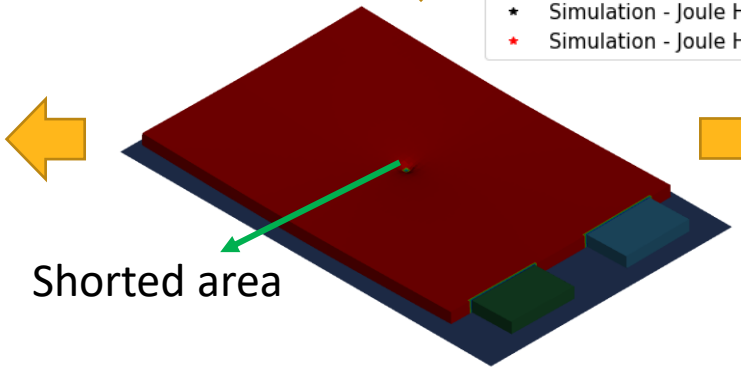


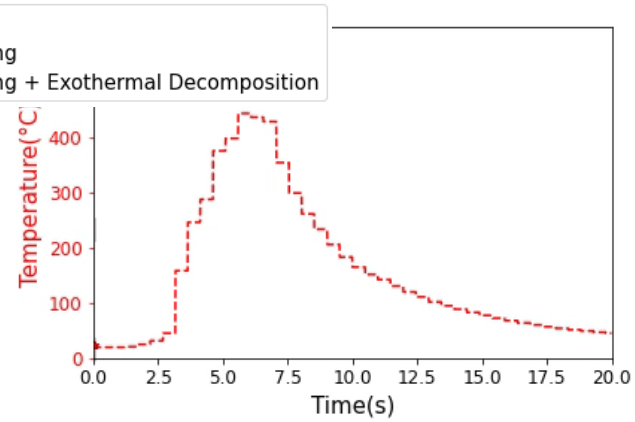


Internal shorts triggered when reaching mechanical deformation threshold

Electrical





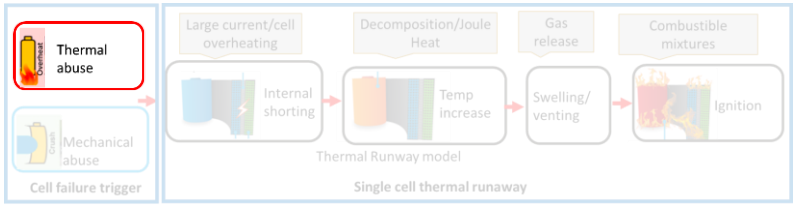


Thermal

Short resistance is used to replace regular resistance in LS-DYNA *EM solver to simulate voltage drop as internal shorts occurs.

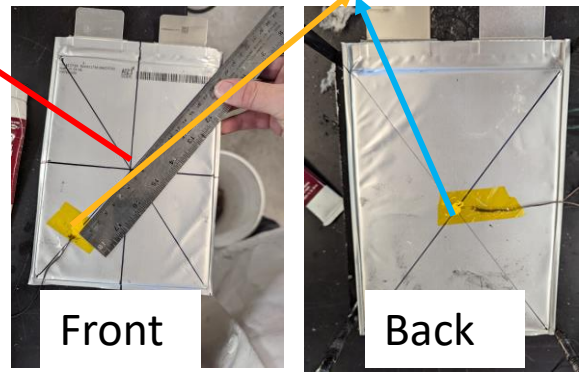
- Additional heat source is triggered to consider TR event;
- Rapid temperature increment during TR is captured;
- Heat release is required to consider cooling.

Cell Thermal Abuse - Experimental Test

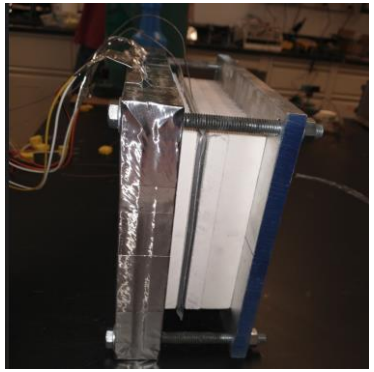


Heater placed at cell center.

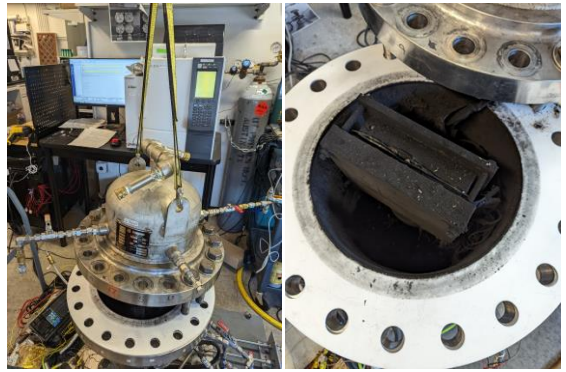
2 temp. probes used for temp. measurement.



Cell is placed between plates with load cell attached at side.

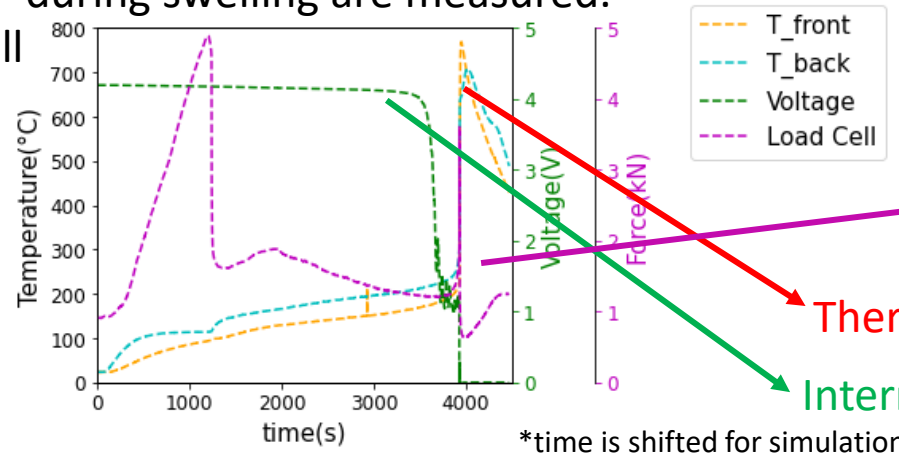


Setup is placed within pressure vessel for thermal runaway test.



Voltage, temperature and cell's force during swelling are measured.

From Cell

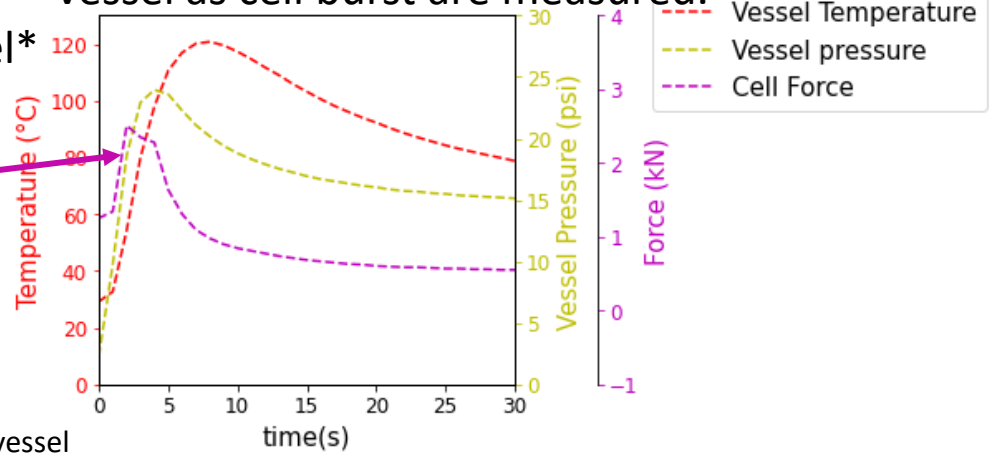


Thermal runaway

Internal shorts

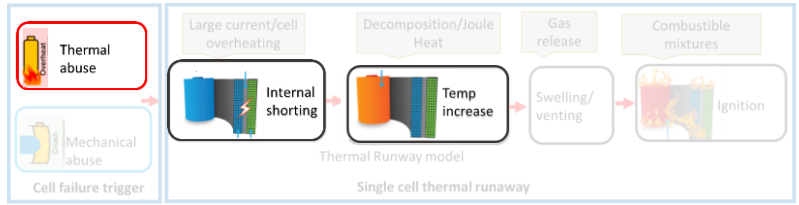
Pressure and temperature released into vessel as cell burst are measured.

From Vessel*

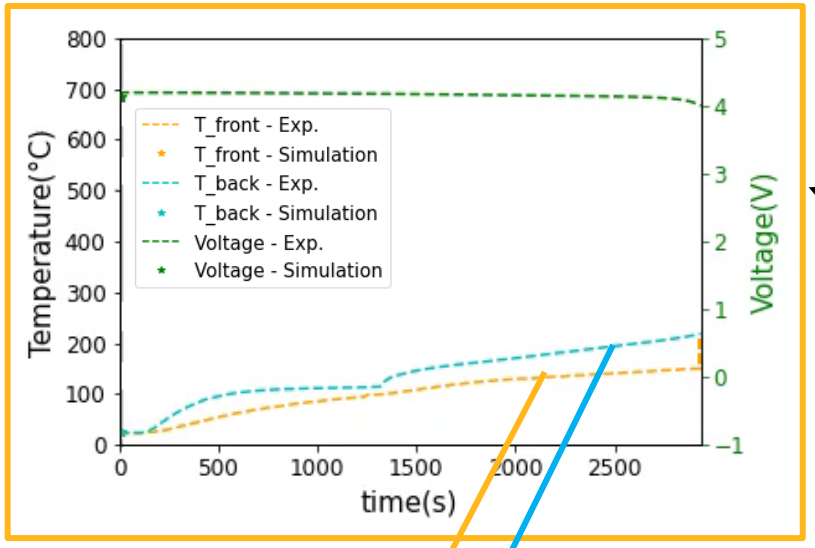


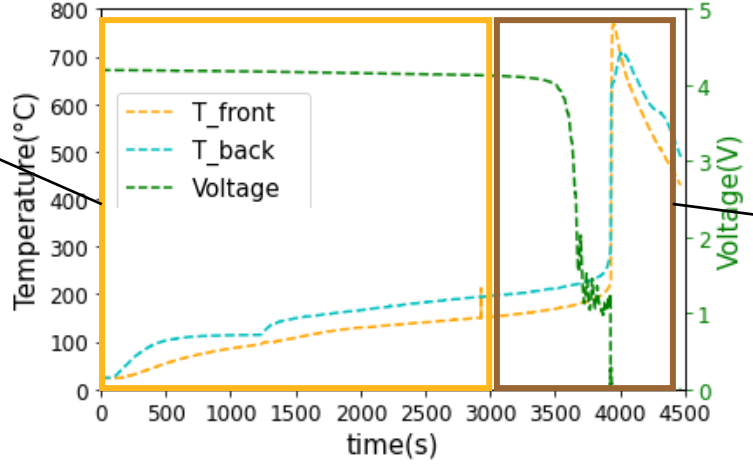
*time is shifted for simulation, time at 0 = gas entering vessel

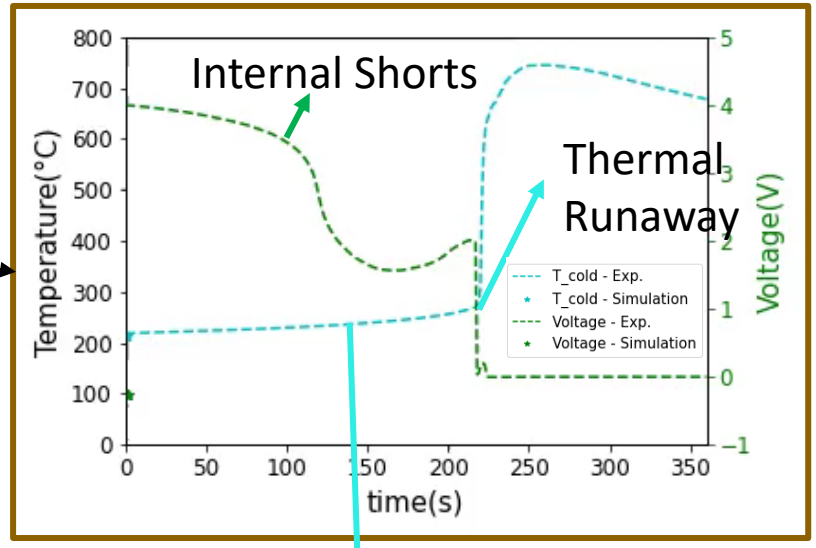
Cell Thermal Abuse - Simulation Results

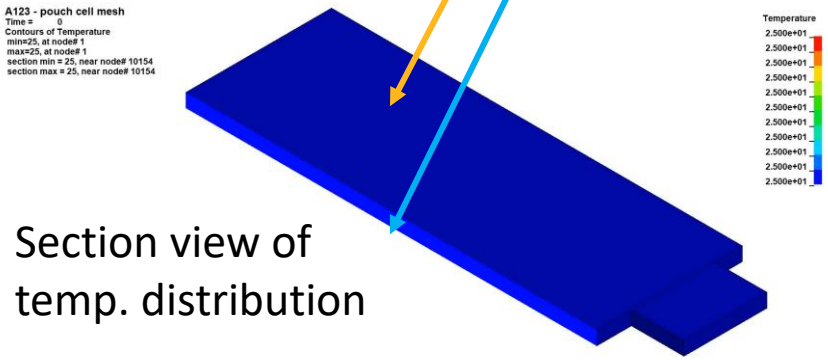


Pre-Internal Shorts

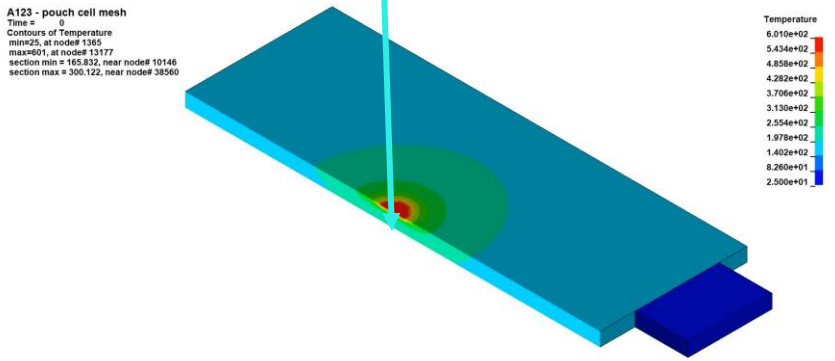








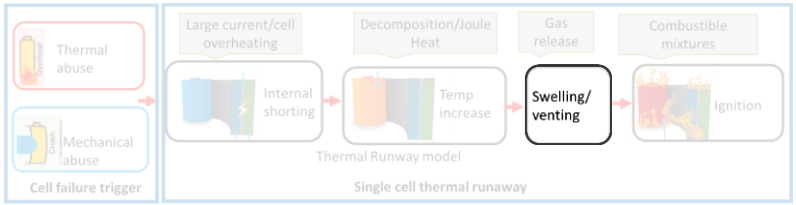
Section view of temp. distribution



Cell's in-plane and through-thickness thermal conductivities are optimized during the heating simulation.

During internal shorts, cell stays stable for a while before entering thermal runaway.

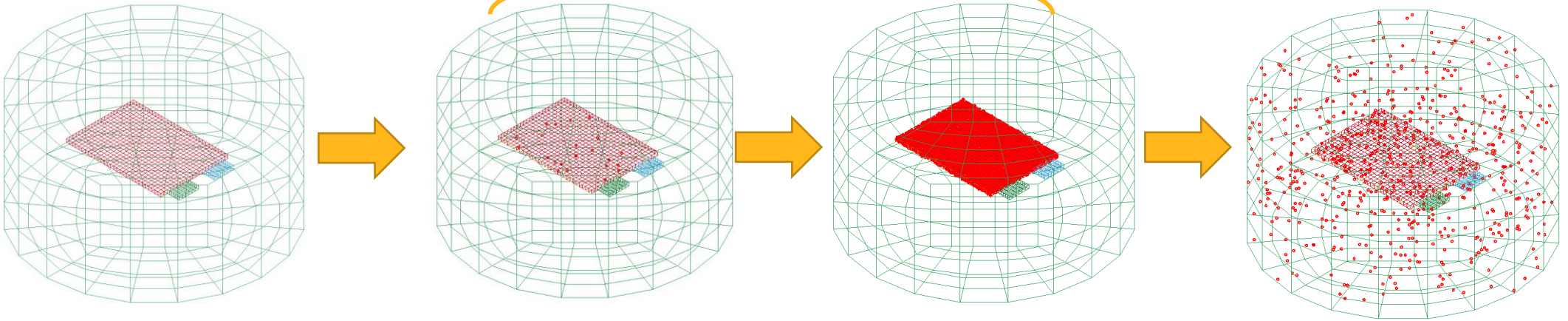
Gas Released in Pressure Vessel Simulation



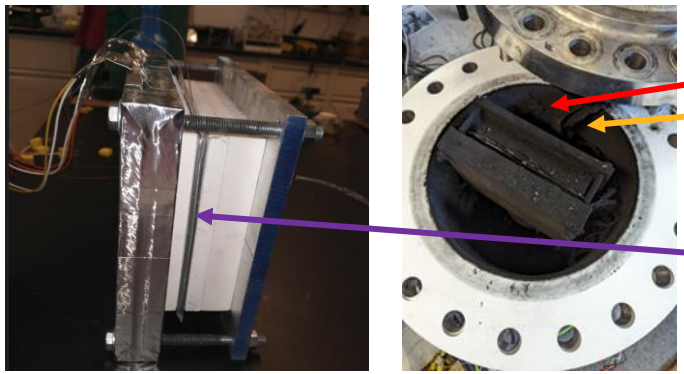
Cell is placed within vessel, sandwiched in between *RIGIDWALL (not shown)

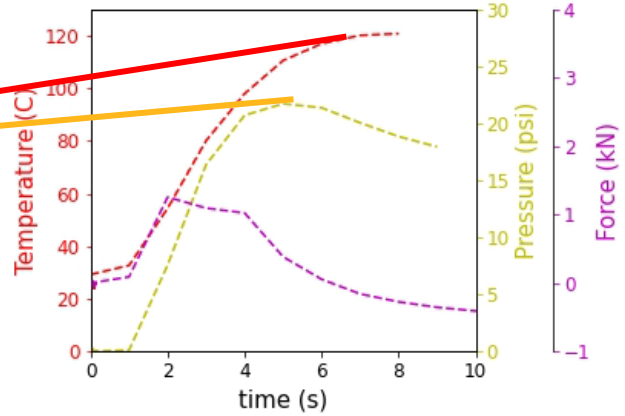
Gas is generated & accumulated within cell

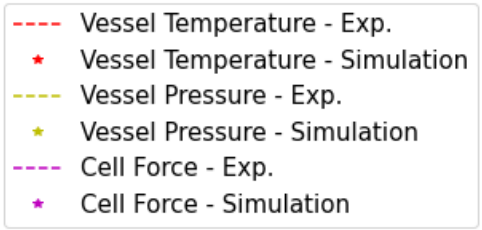
Cell bursts and gas is released into vessel



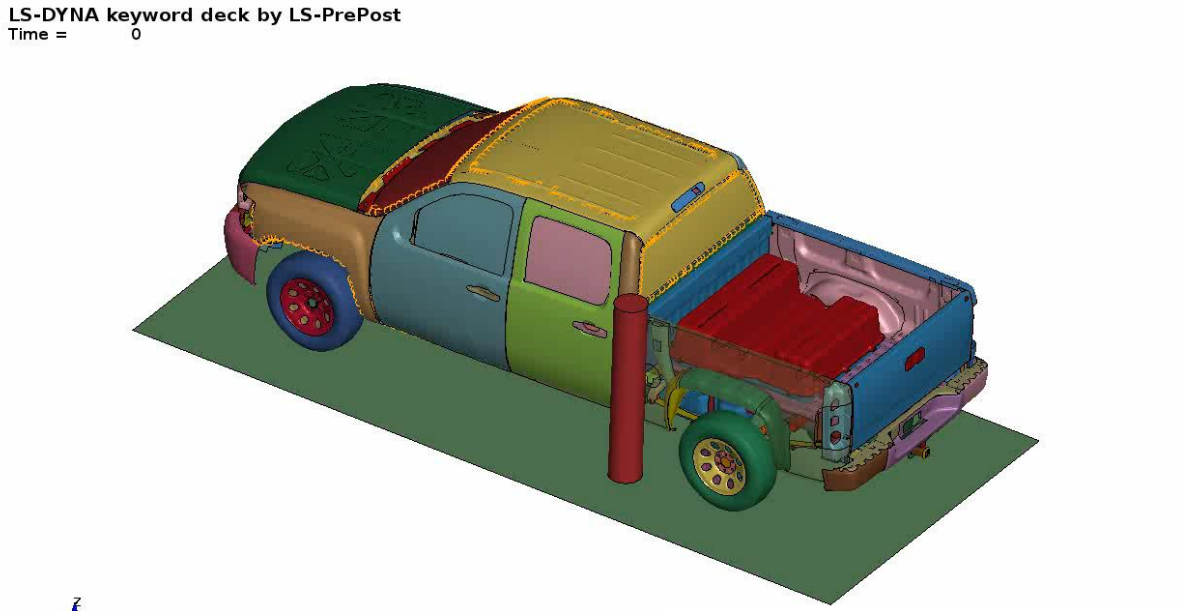
Particle method in LS-DYNA is used to simulate cell swelling and venting process in a thermal abuse condition;
Future work including thermal abuse of battery module and heat distribution within vessel is work in progress.



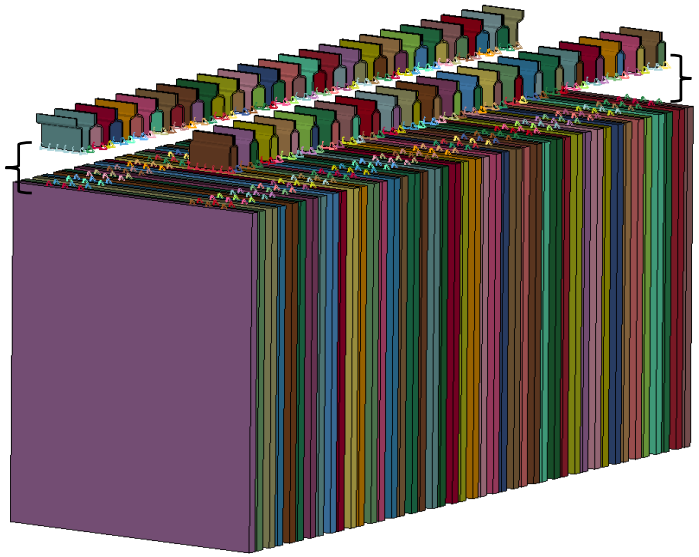




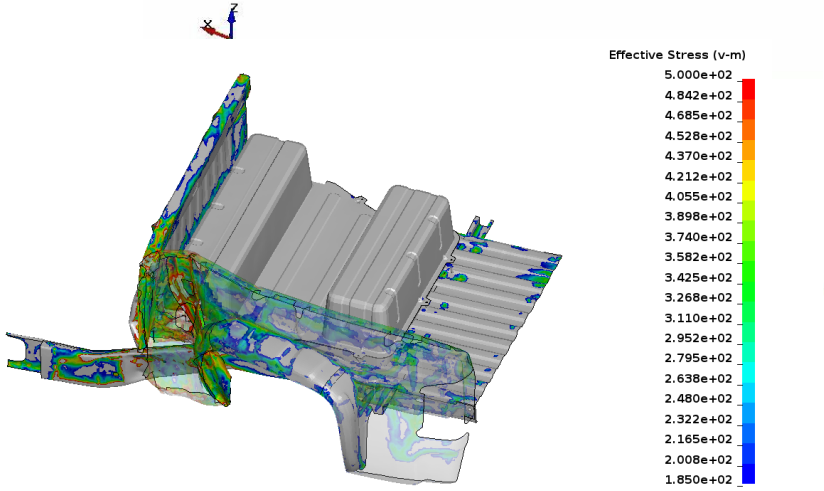
Battery in Vehicle Crash

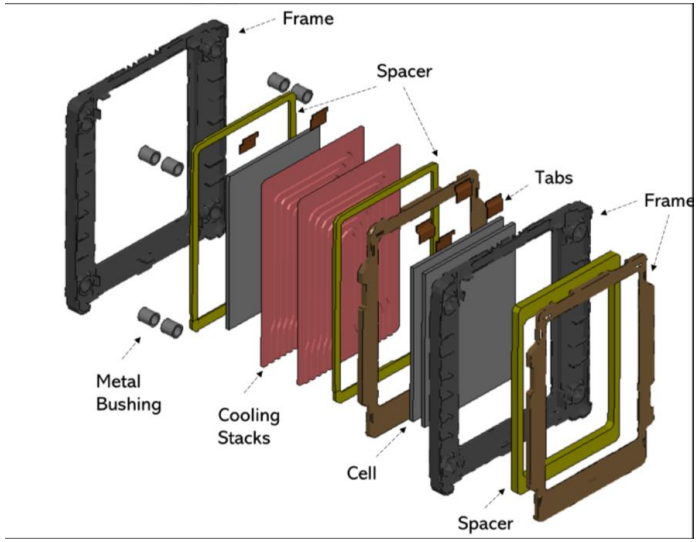


-ve Tabs connected to the cells negative



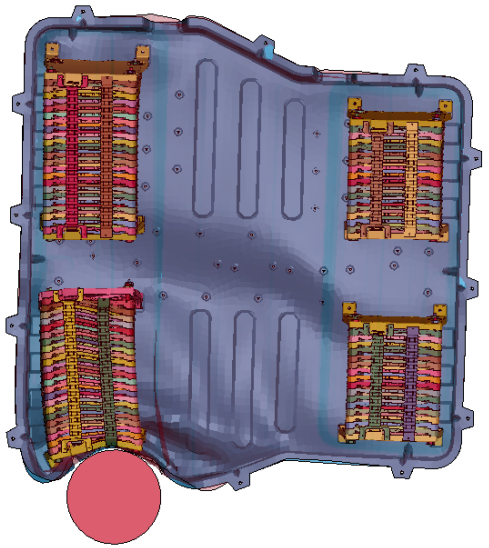
+ve Tabs connected to the cells positive

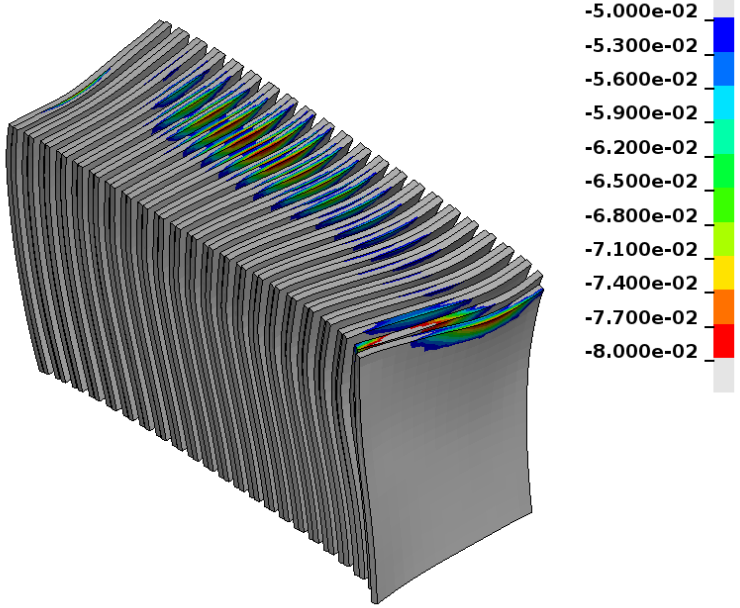


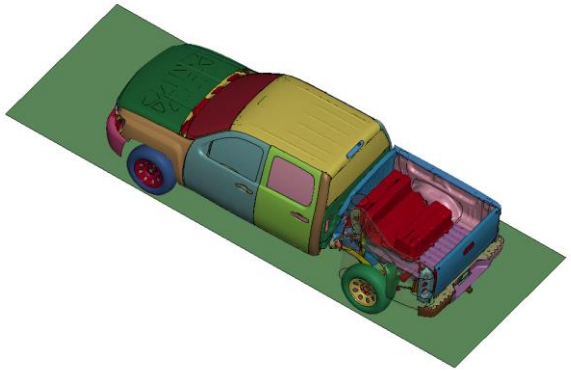


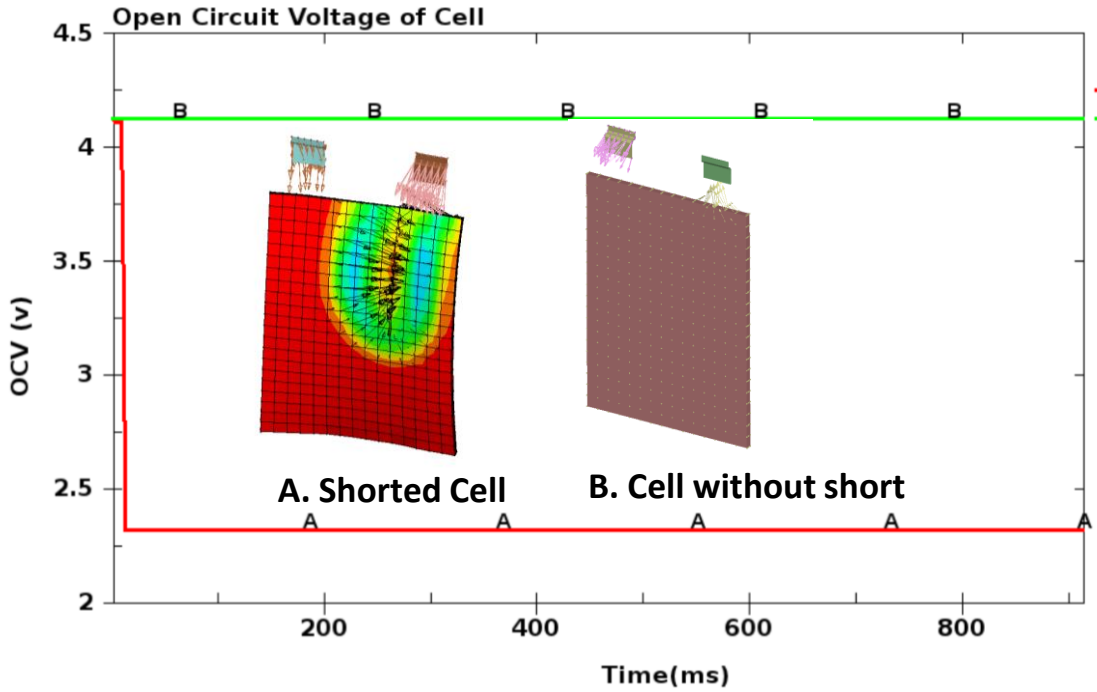
Battery in Vehicle Crash

Short condition lowered to demonstrate mechanically induced short





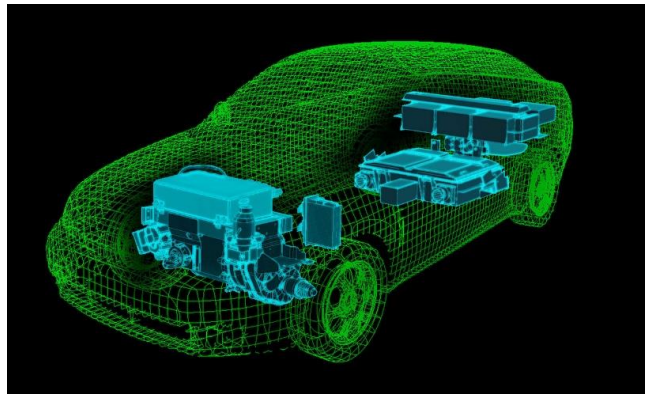


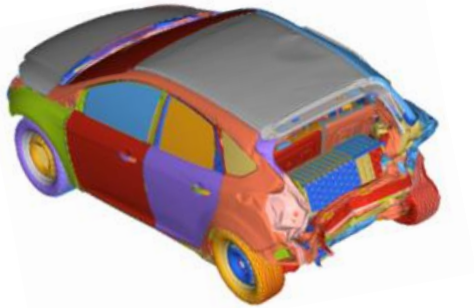


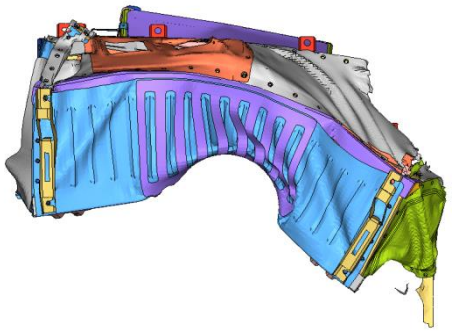
Battery structural design did a good job protecting cells, so no internal shorts in this case. Failure criterion lowered to trigger internal short for demonstration purpose

Conclusion

- LS-DYNA is a Multiphysics code : A framework of battery safety modeling that couples mechanical, thermal, electrical and electrochemical responses of batteries is developed.
- The development was done in collaboration with industrial partner (Ford), but is available to all users.
- To our knowledge no other code has this multi-physics capability, especially not the coupling between the mechanics and the rest
- Simulation solvers themselves rely on experiment tests to characterize their equations => effort needed across industries and academia to bolster our collective knowledge. Ansys has started this effort







Thank you !