# Thermal Runaway in Electric Vehicle Crash Simulation using LS-DYNA

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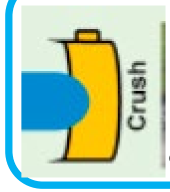
# Vehicle Safety

- 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

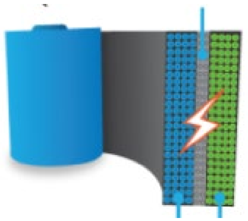

Thermal abuse




Mechanical abuse

**Cell failure trigger**

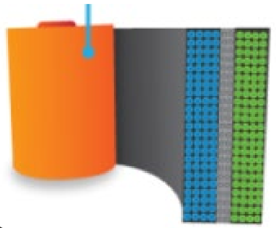
Large current/cell overheating



Internal shorting

Initial Joule Heating

Decomposition/Joule Heat



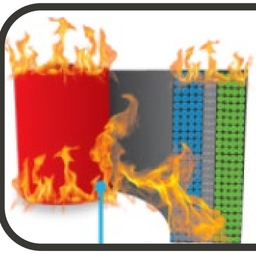
Temp increase

Exothermal reaction model

Gas release

Swelling/ venting

Combustible mixtures



Ignition

Ignition model

**Single cell thermal runaway**

**Cell to Cell Propagation**

Thermal contact

# Parameters needed to model a battery abuse in a car crash

- **Mechanical**: Material model
- **EM**: Equivalent circuit parameters / electrochemistry model parameters
- **Thermal**: Heat capacity, thermal conductivity
- **Mechanical + EM  / Thermal + EM**: Onset of internal short, short resistance
- **Mechanical + Fluid**: Gaz ejection from cell going to thermal runaway (pressure, composition, …)

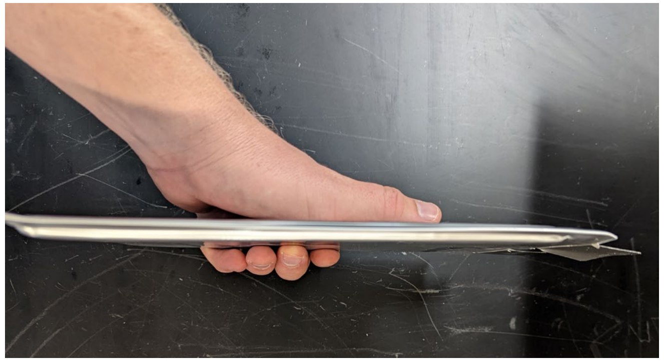
These can be found by reverse engineering on one or several cells and applied to a full battery in a car crash simulation

# Array of tests to get the simulation parameters

- Cell Electrical characterization
- Thermal abuse on one cell
- Thermal abuse on an array of 5 cells
- Static mechanical abuse
- Dynamical mechanical abuse

# 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.

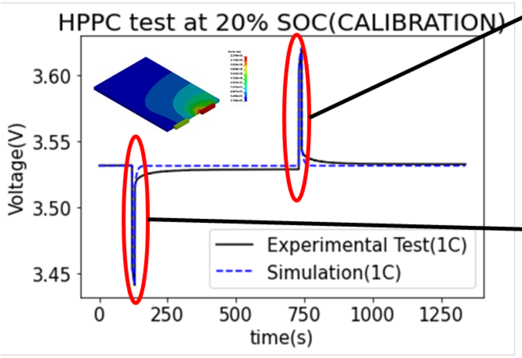
# Cell electrical characterization (high C-rate testing, HPPC)

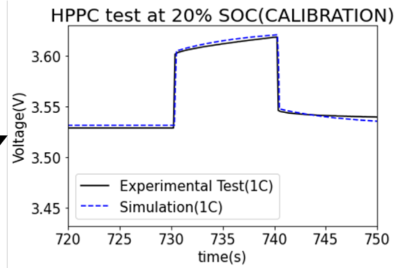
# Cell Electrical Characterization

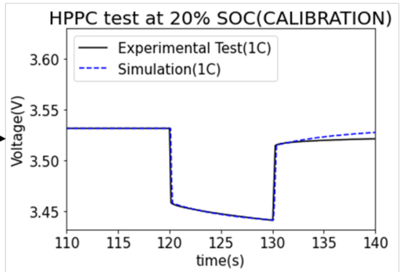
Electrical

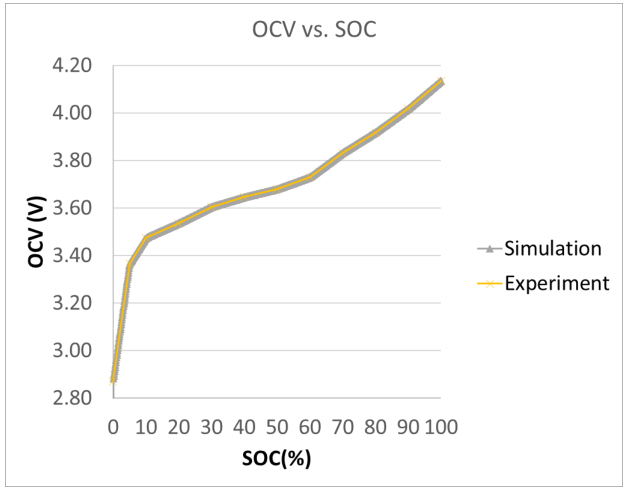
- Electrical behavior of the cell is represented by equivalent distributed circuit (Randles Circuits).
- Randles parameters (as a function of SOC level and temperature) for cell model input are obtained from HPPC/capacity test*.
- For the HPPC test, cell is rapidly charged/discharged and slowly discharged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

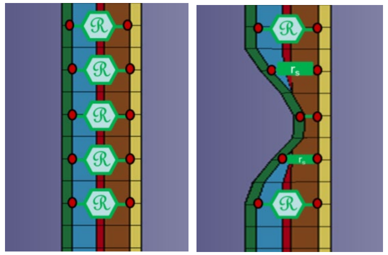
Randles parameters are verified in HPPC simulation using BATMAC model in LS-DYNA.



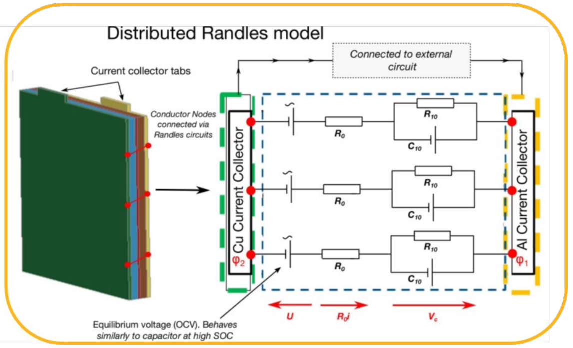



In LS-DYNA:




*Performed internally by ANSYS testing team – formerly DfR Solutions

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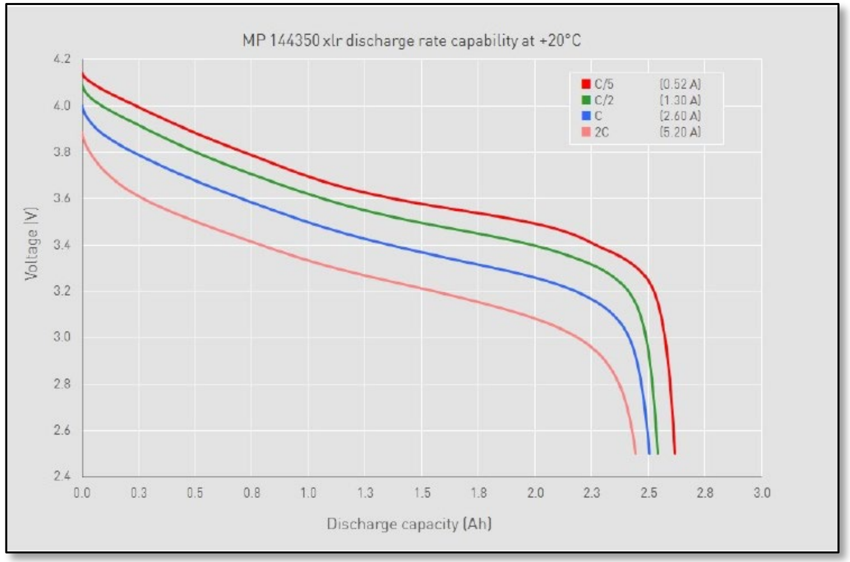
# Battery Testing

- **Background:** Battery performance and characteristics greatly influence reliability. Tests include capacity over the operational temperature range, cycle life and high C-rate (power) testing, hybrid pulse power characterization (HPPC) testing for extracting simulation parameters.
- **Application:** These tests ensure that a selected battery can meet the longevity and power demands of an application. The test results can also be the inputs for battery simulation.
- **Capability:** Ansys has two battery cyclers: a 500A, automotive battery cycler; and a 10A cycler

Example Battery Test Data




Battery Cycler

# A Generic Battery APP is being developed at Ansys

- Work for any Cell Format
- Automatically convert HPPC test curves to model input
- Define characterization test based on Cell Format
- Automatically convert mechanical indentation test to material input

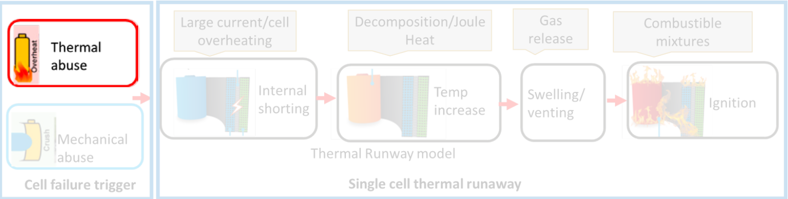

1 Cell Formats

2 HPPC Test

3 Mechanical Indentations

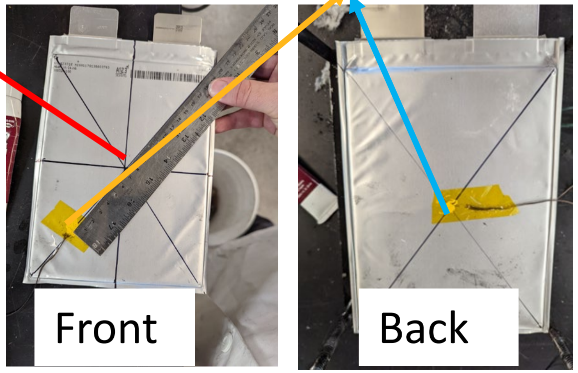
# Thermal abuse on one cell

# Cell Thermal Abuse - Experimental Test

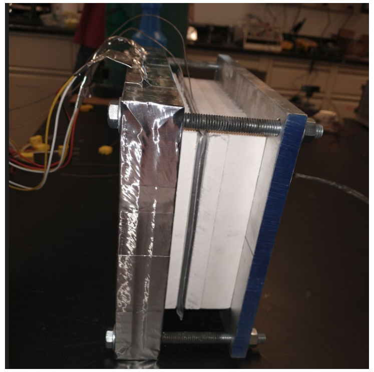



Heater placed at cell center.

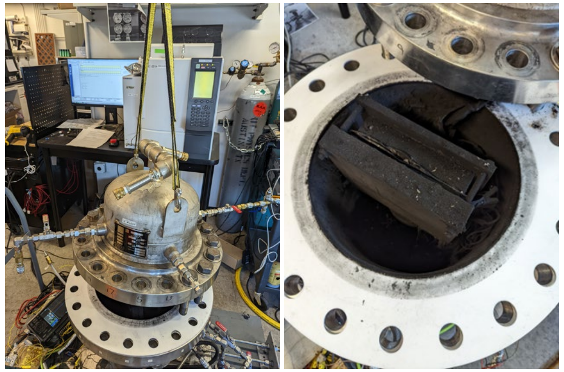
2 temp. probes used for temp. measurement.




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

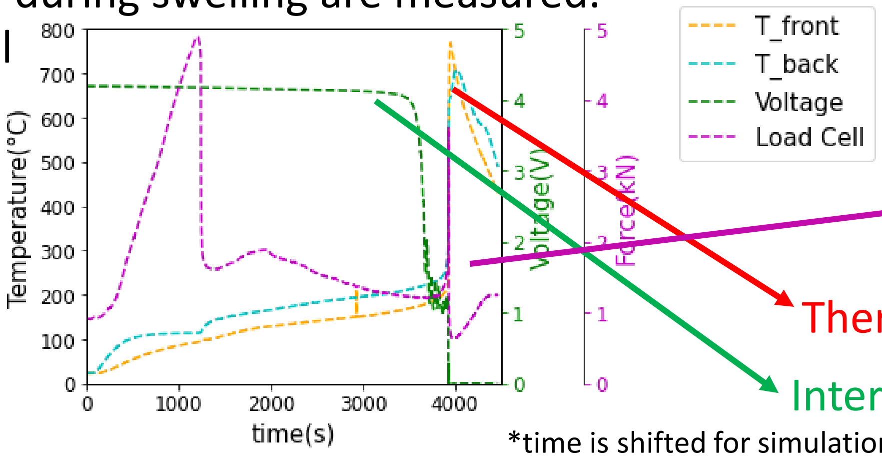


Setup is placed within pressure vessel for thermal runaway test.



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

From Cell

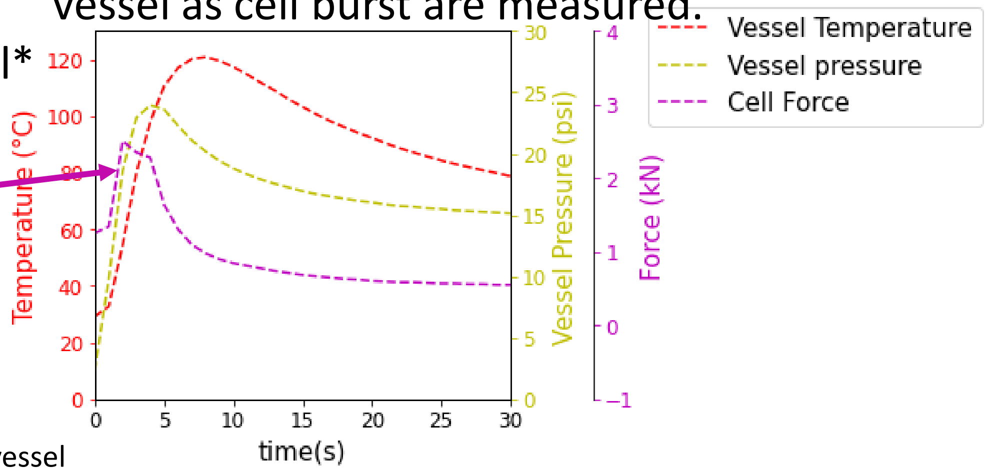



Thermal runaway

Internal shorts

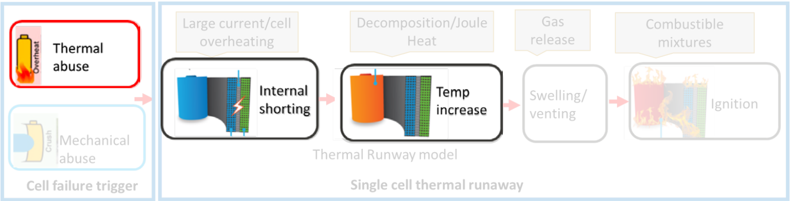
Pressure and temperature released into vessel as cell burst are measured.

From Vessel*

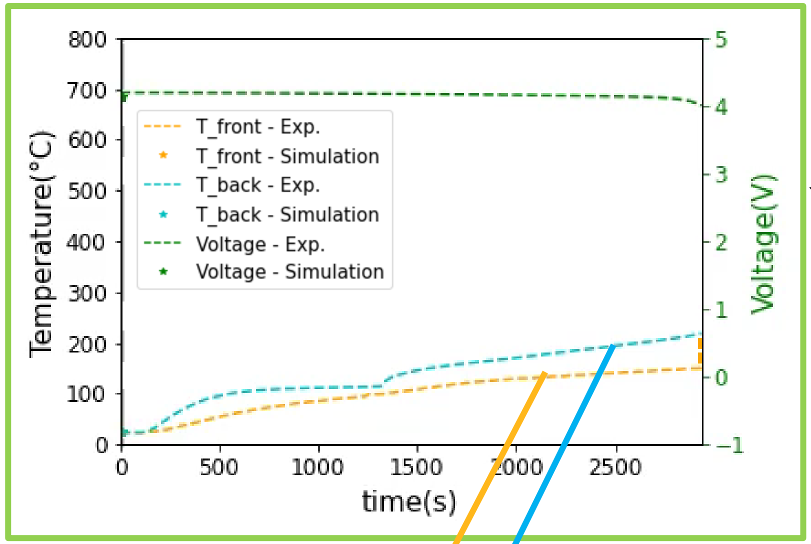


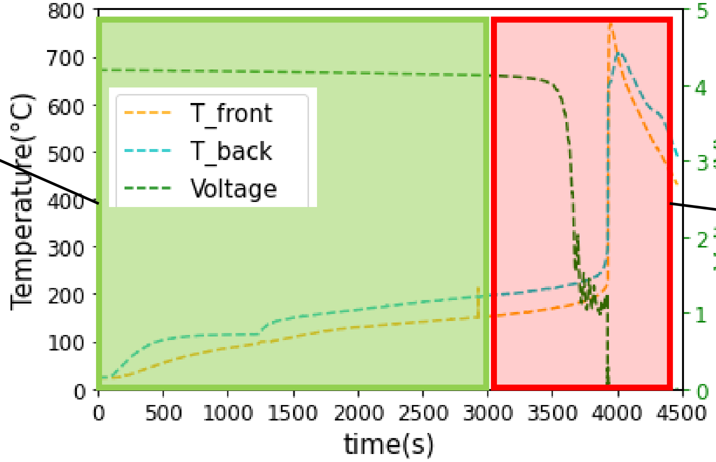

*time is shifted for simulation, time at 0 = gas entering vessel

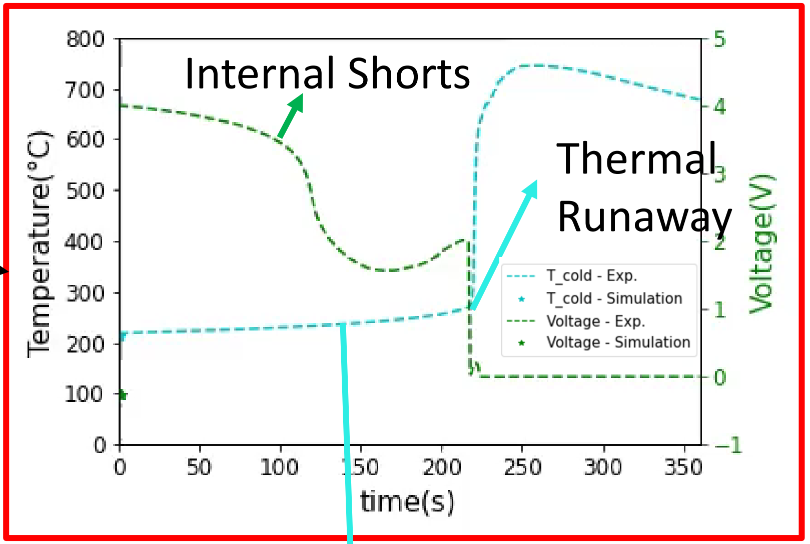
# Cell Thermal Abuse - Simulation Results

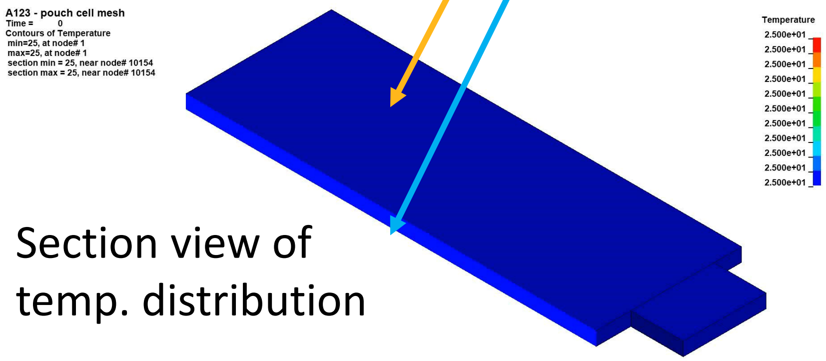



## Pre-Internal Shorts

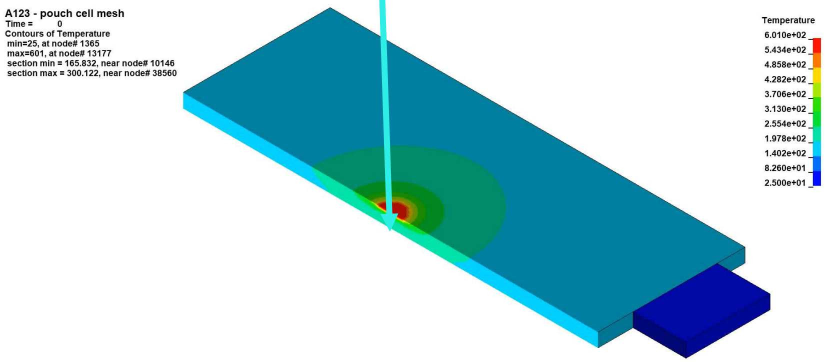



Section view of temp. distribution




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.

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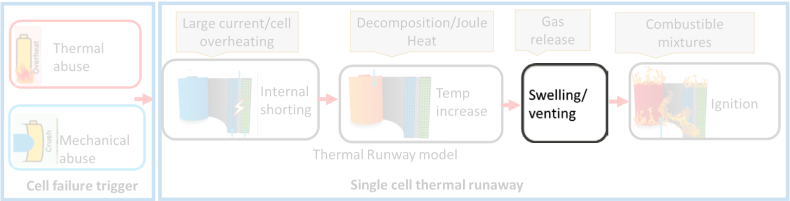
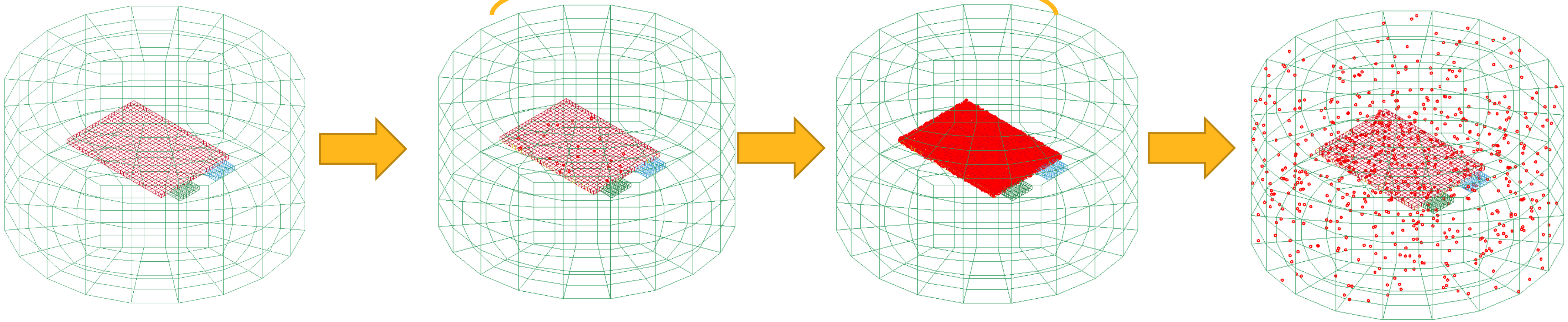
# Gas Released in Pressure Vessel Simulation



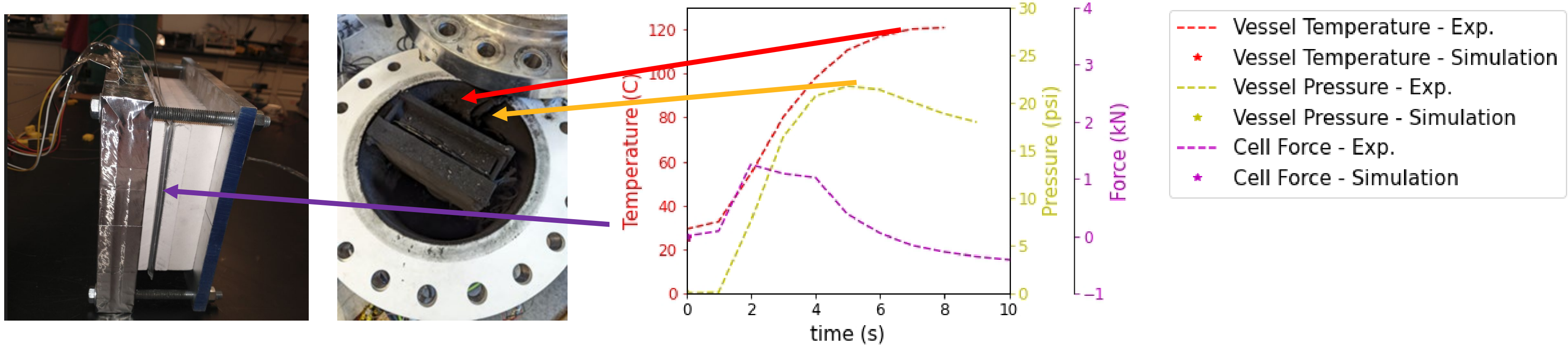

Cell is placed within vessel, sandwiched in between *RIGIDWALL (not shown)

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.



# Thermal abuse on An array of 5 cells



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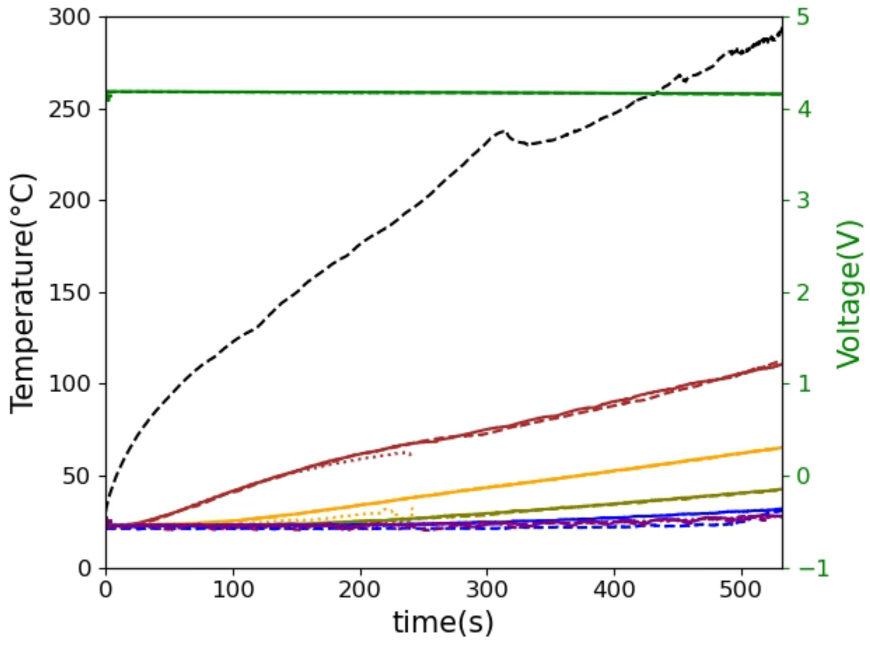
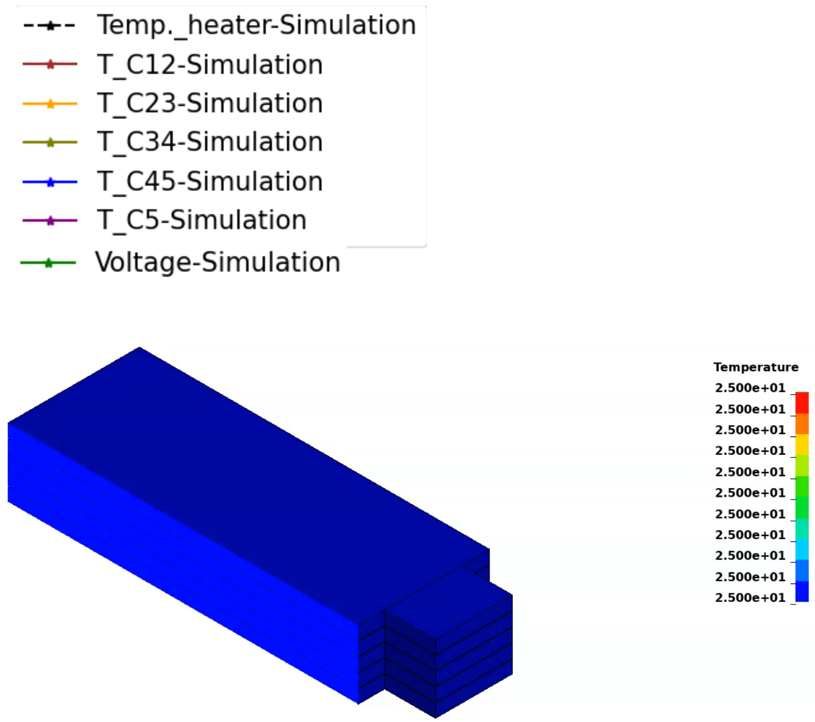
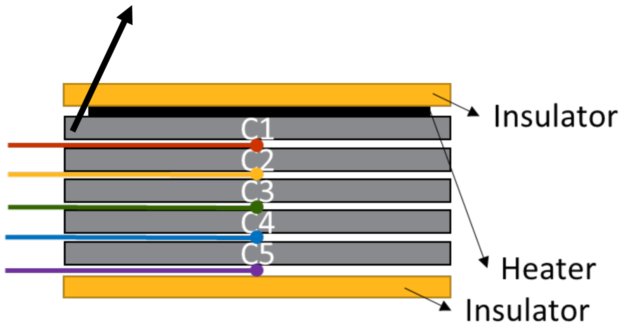
# Cell Array Thermal Abuse Simulation Results–Pre-Internal Shorts

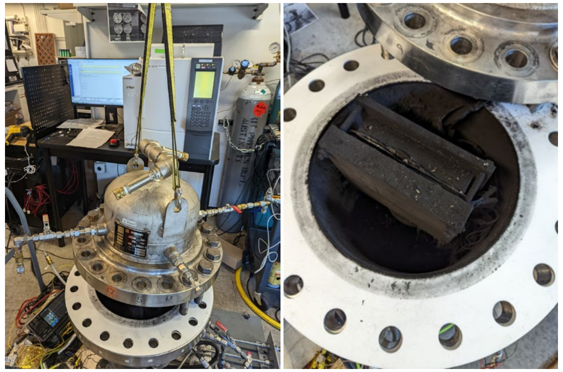
- A stack of 5 cells is heated inside a pressure vessel to achieve thermal runaway (TR).



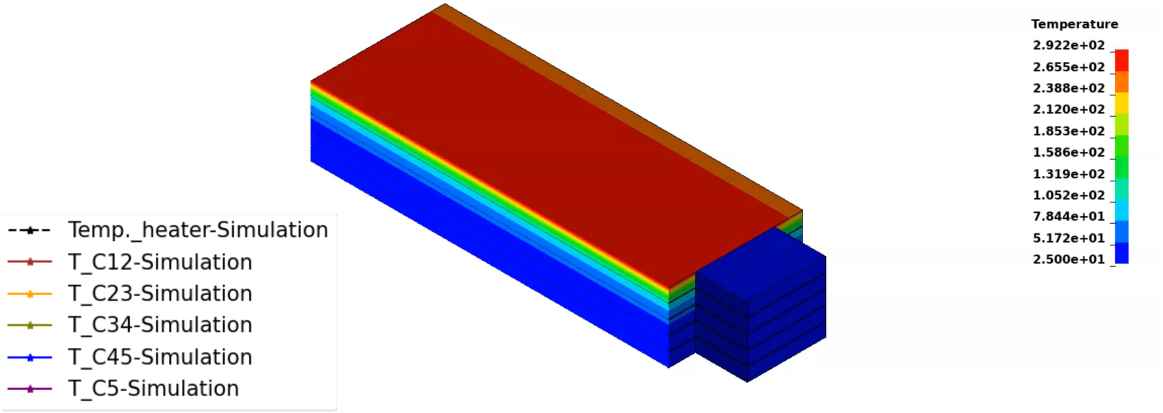

C1 is the triggered cell; Heater is turned off once TR occurs

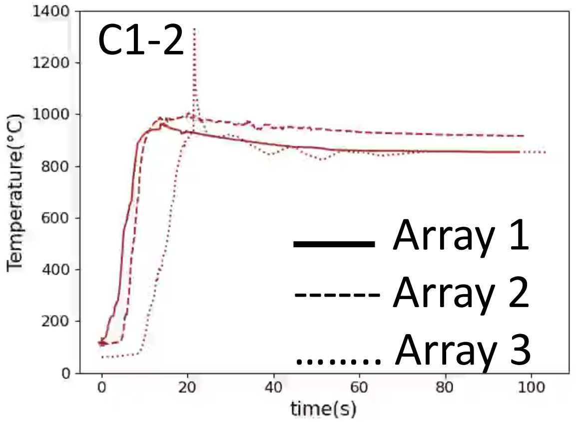


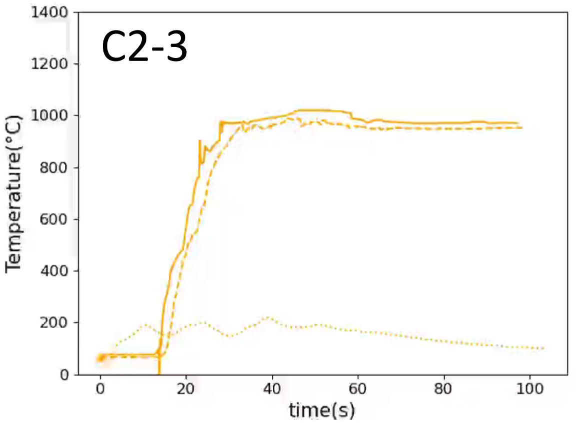



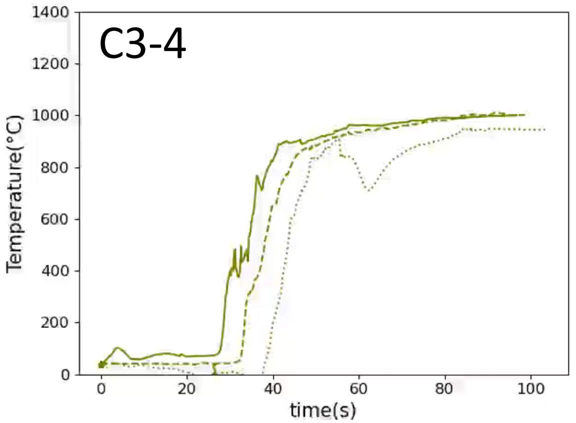
# Cell Array Thermal Abuse Simulation Results–Post-Internal Shorts

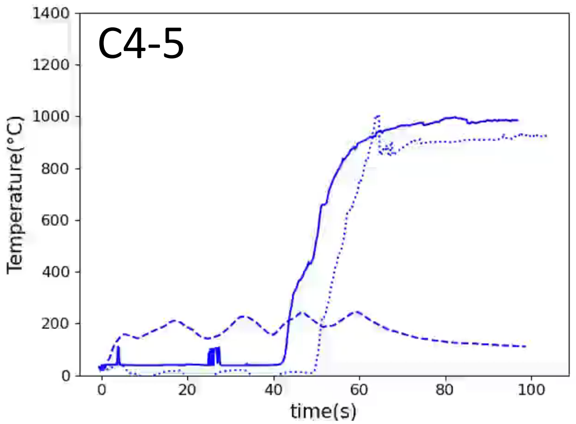
- Simulation is compared with 3 repeated test results.

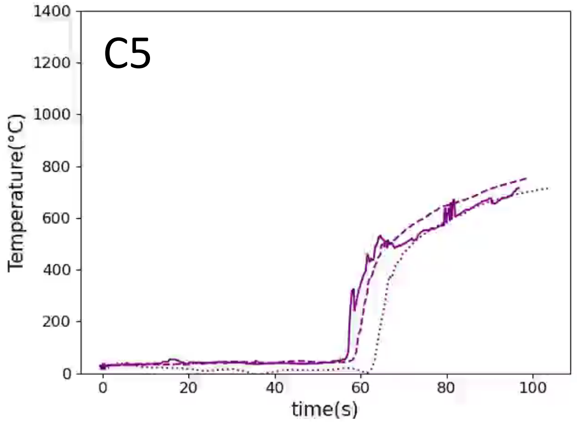


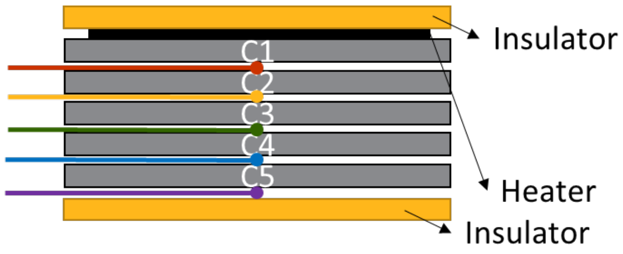



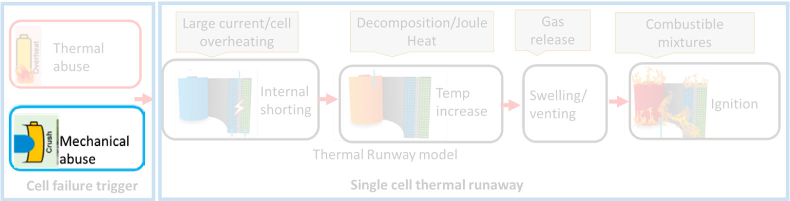



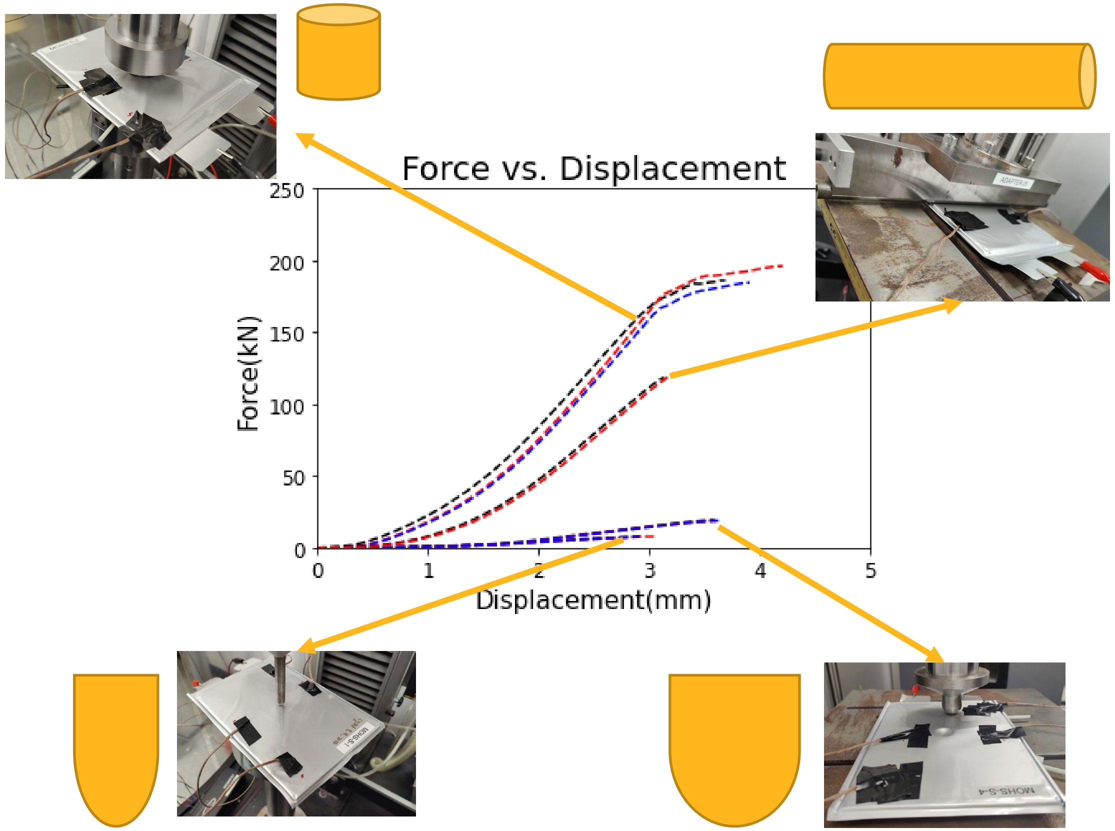



# Static mechanical abuse

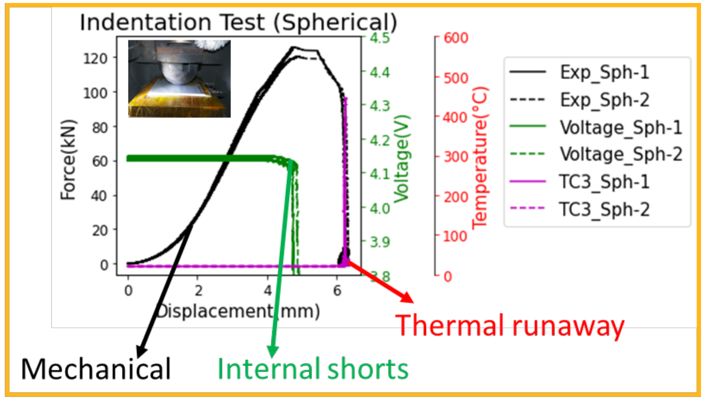
# Cell Mechanical Abuse - Experimental Test



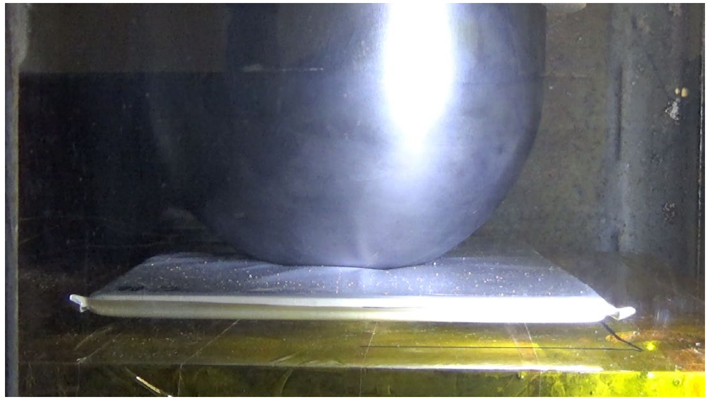

Various mechanical tests were conducted to calibrate and validate cell's mechanical properties.




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









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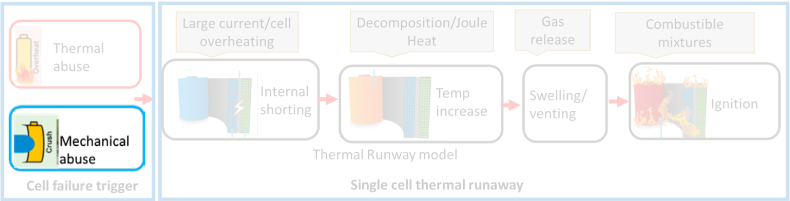
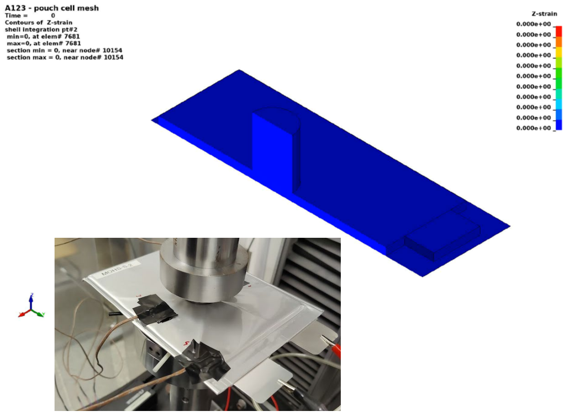
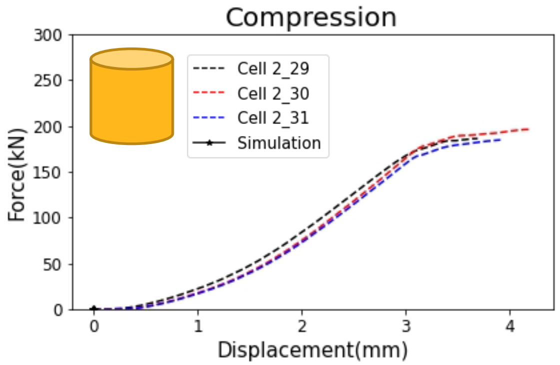
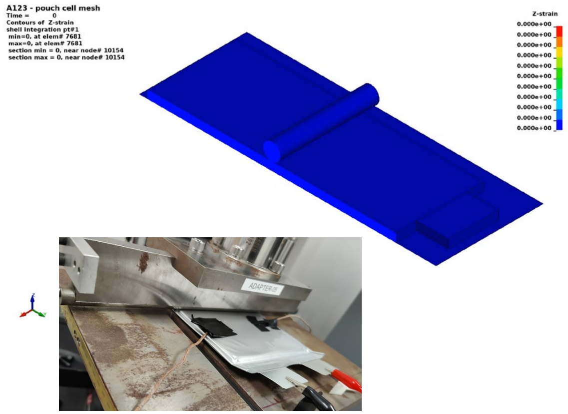
# Cell Mechanical Abuse - Simulation Results

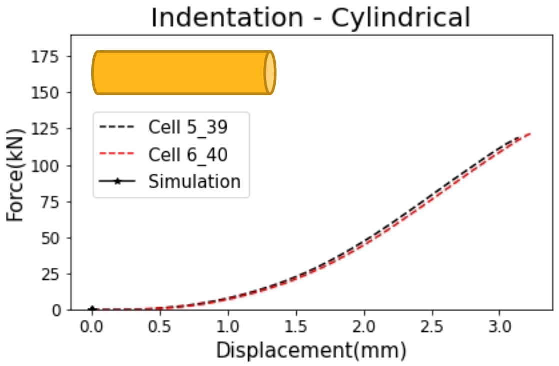


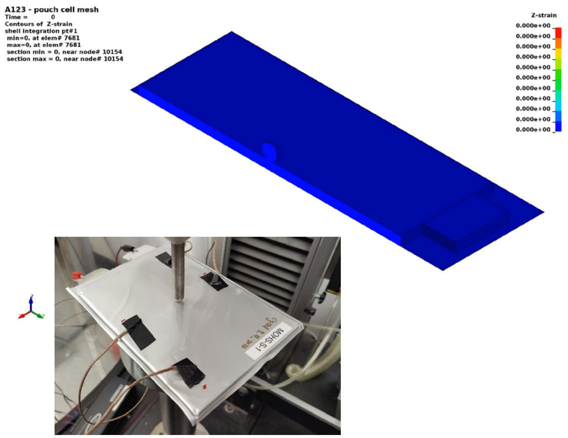

Crushable foam (*MAT_063) material model in LS-DYNA is used to simulate cell's mechanical properties.
In search of common failure criteria across various loading conditions.

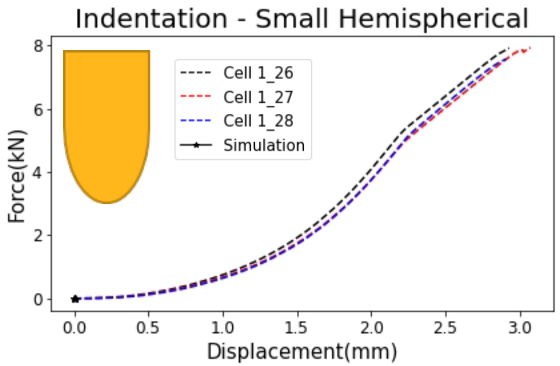


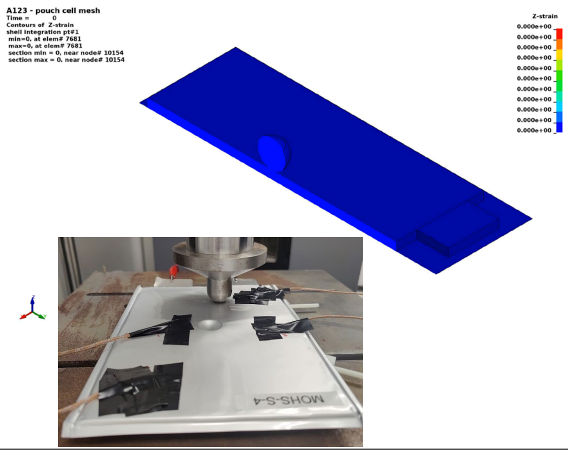



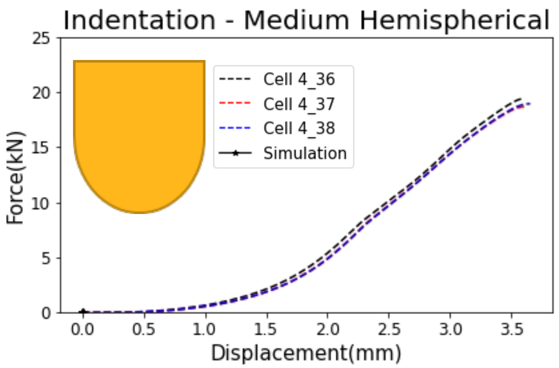

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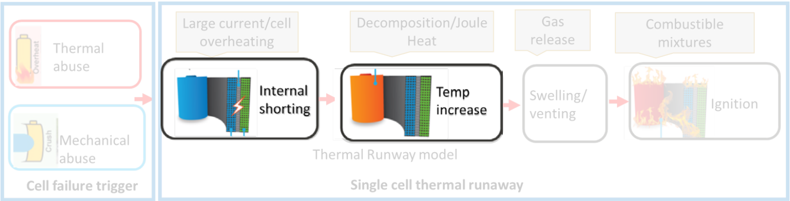
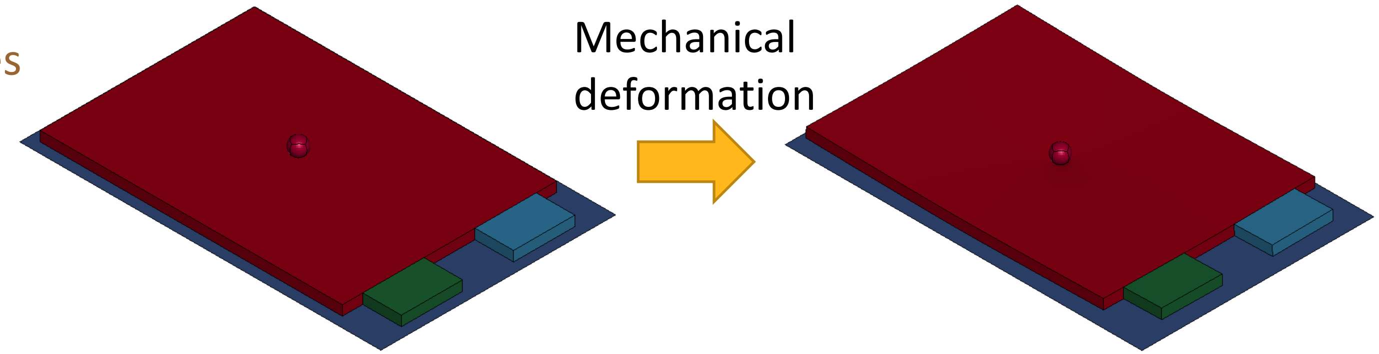
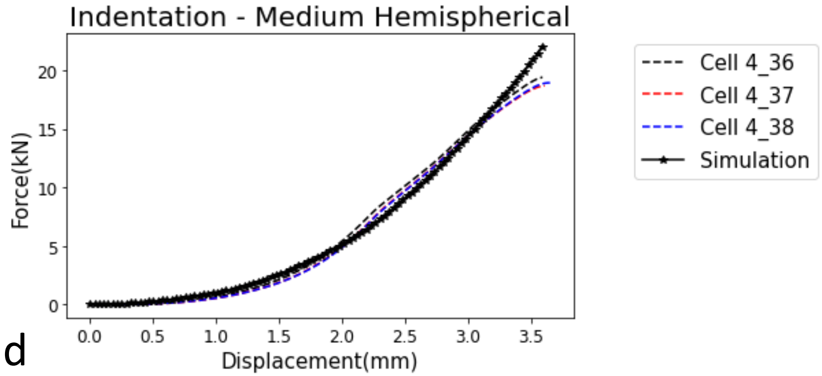
# Cell Mechanical Abuse - Simulation Results



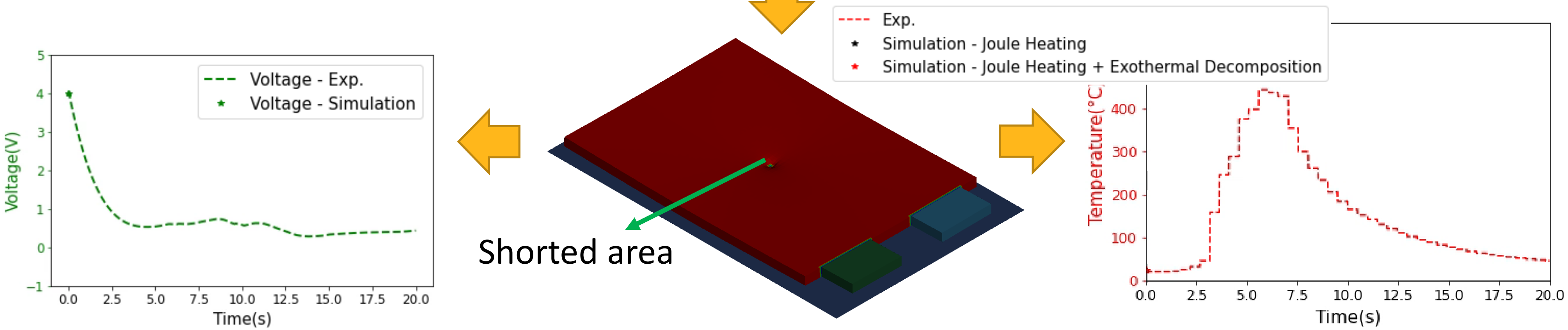

Structures




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.

# Dynamic mechanical abuse



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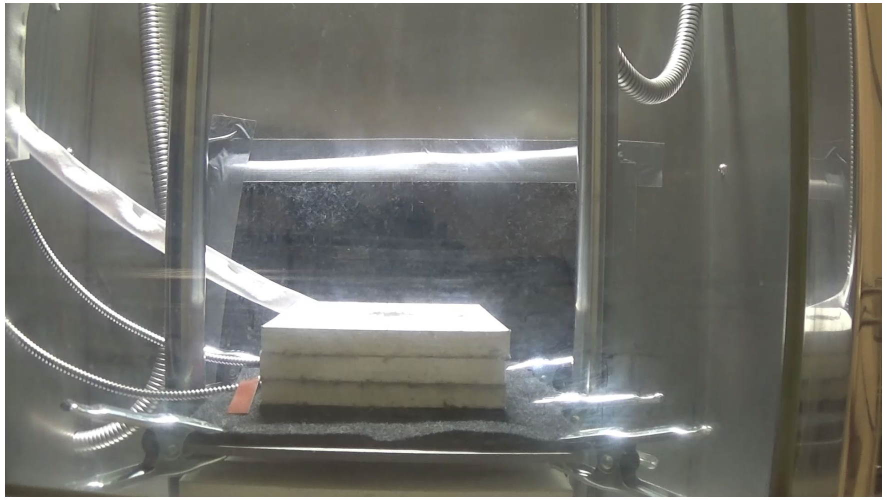
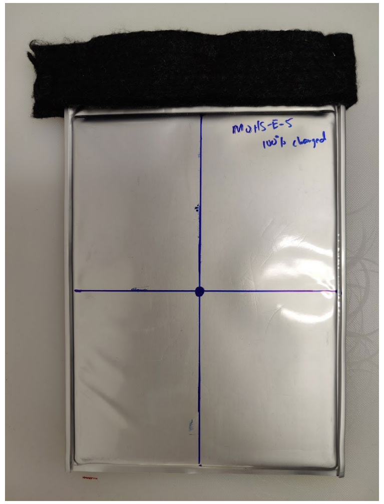
# Cell Dynamic Loading - Experiment

- Cell response under static loading (<1 mm/min) to build internal knowledge and solver improvement
- Dynamic impact testing (>1m/s) on cells to fulfill automotive crash application
- Dynamic testing is completed with Temple University (Philadelphia, USA). Mechanical, voltage and temperature data are collected for multi-physics model validation

100 SOC cell – 3m/s impact



Before



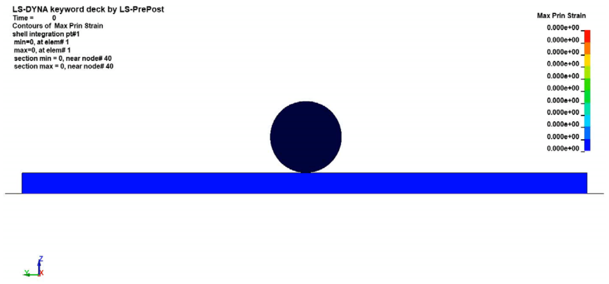
After

| Loading direction | SOC level | Indenter size | Loading rate | Sample size | Completion |
|---|---|---|---|---|---|
| Through thickness | 100 | ⌀12.7mm | 1 m/s | 2 | 2 |
| | | ⌀25.4mm | 3 m/s | 2 | 2 |
| | 50 | ⌀12.7mm | 1 m/s | 2 | 2 |
| | | ⌀25.4mm | 3 m/s | 2 | 2 |
| | 0 | ⌀25.4mm | 3 m/s | 2 | 2 |

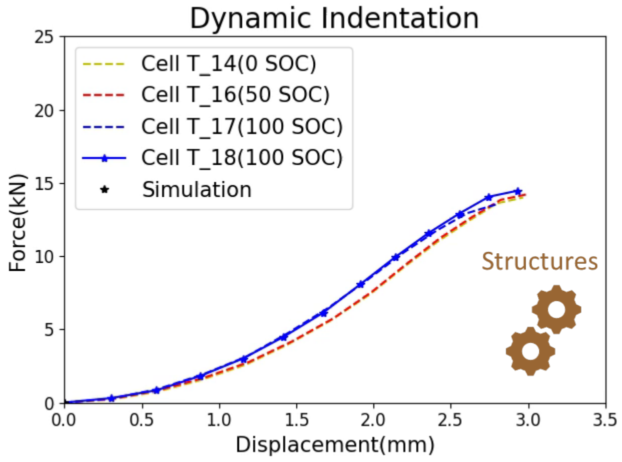
# Cell Dynamic Loading - Modeling

- Preliminary simulation results show previously developed methodology for the cell multi-physics model validation is also applicable in dynamic loading event
- Model validation against other loading rates and cell's state of charge (SOC) is work in progress

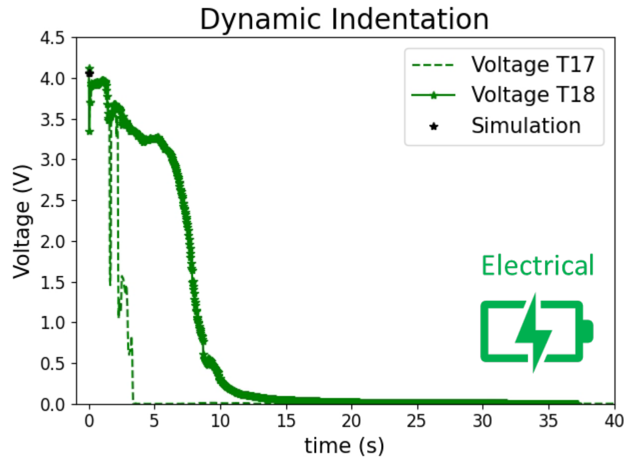
Dynamic impact of cell (3m/s)



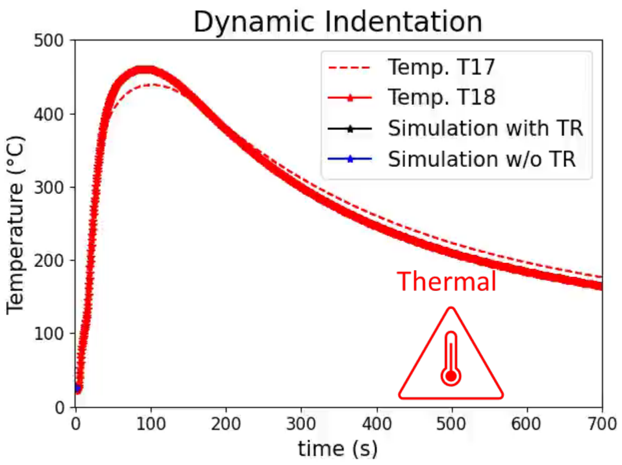
Mechanical




Electrical:
Internal Shorts (IS)




Thermal:
Thermal Runaway (TR)



# Conclusion

- Array of tests on one or a few pouch cells allowed us to get the parameters needed for a full battery in a car crash
- These tests can be reproduced for other kinds of cells (cylindrical, prismatic, different chemistry), allowing to predict the behavior of a full battery on an eV car crash.
- Sharing test results from the industry or academia can bolster our collective knowledge and understanding of battery abuse and its consequences

# Thank you !