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Multiphysics Simulation of Battery Cells and Packs for Electric Vehicles

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Simulation for EV Battery Development

- New battery technologies must satisfy certain targets prior to commercialization:
  - Safety
  - Cost
  - Performance

- Multiphysics simulation can help solve various challenges to meet these targets:
  - Electrochemical
  - Thermal
  - Mechanical

Increasing Battery System Performance

Cell

Cell-to-Module

Module

Cell-to-Pack

Pack

Cell-to-Chassis

Cell-to-Vehicle

Vehicle

Mobile Power

Aircraft

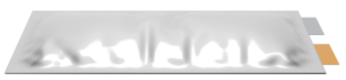
Automotive

Rail

Innovation Drivers:

- Lower Cost
- Lower Weight
- Simpler Manufacturing
- Higher Energy Density
- Smaller Form Factor

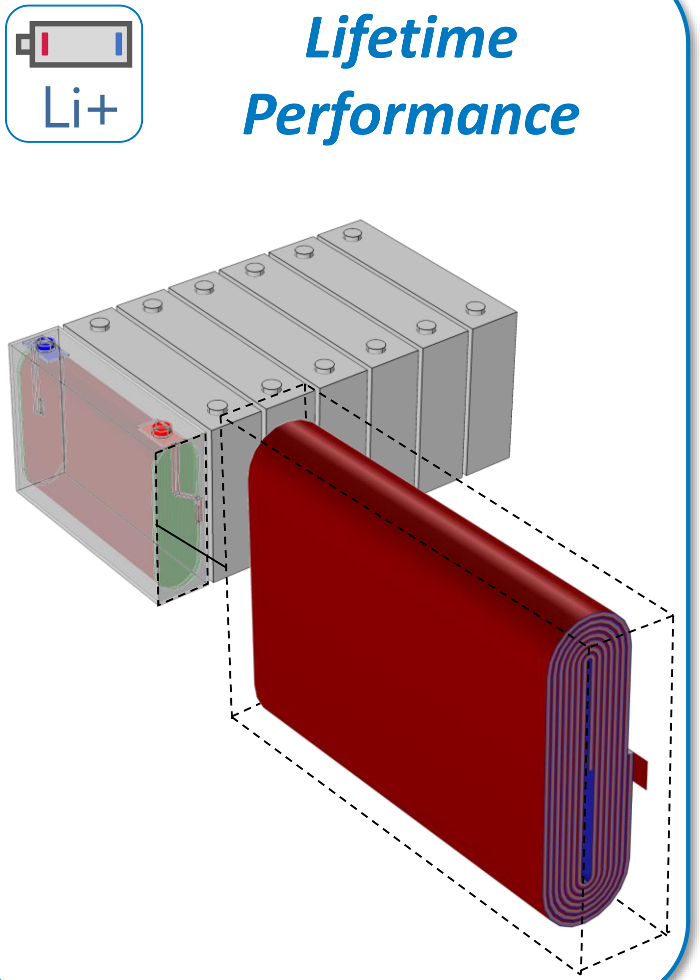
Multiphysics Challenges in Battery Systems



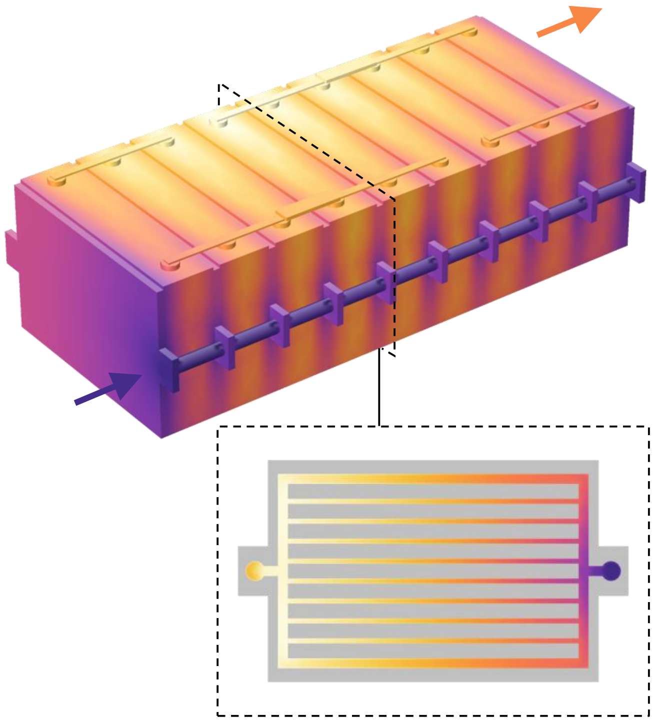
	Electro-chemical	*Thermal*	*Mechanical*
Cell Level	Voltage losses Capacity fade and aging Lifetime performance	Heat dissipation	Volume expansion Internal stresses Delamination and cracking
Module Level	Cell-to-cell state of charge variability Voltage imbalances	Cell-to-cell temperature uniformity Cooling efficiency	Compact form factor Thermal stresses Aging and degradation
Pack Level	State of charge estimation Over-discharge	Module-to-module temperature uniformity Safety and thermal management	Lightweighting Structural adhesives Structural durability

COMSOL Multiphysics® Simulations

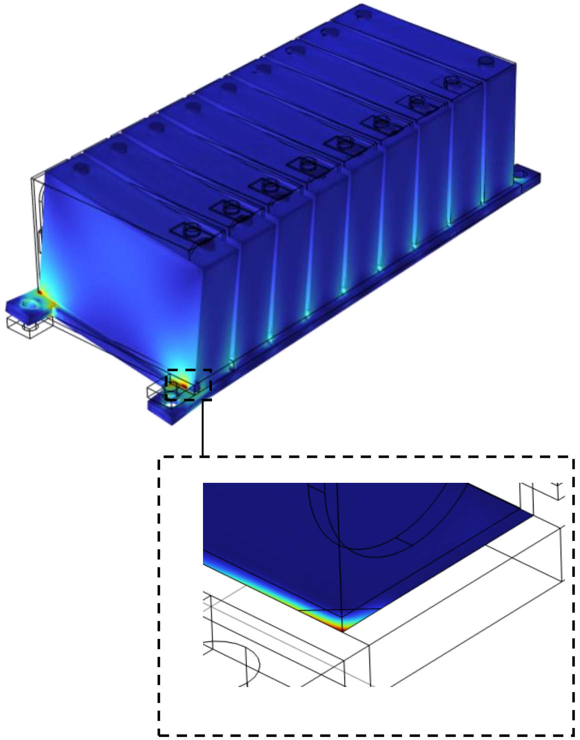
Lifetime Performance



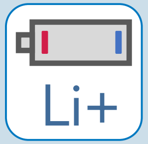
Thermal Management



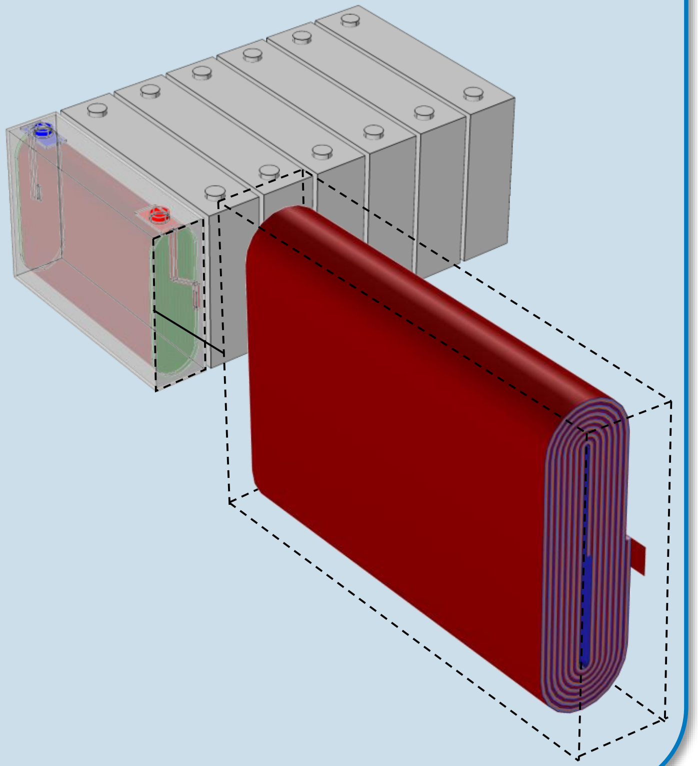
Structural Durability



COMSOL Multiphysics® Simulations



Lifetime Performance

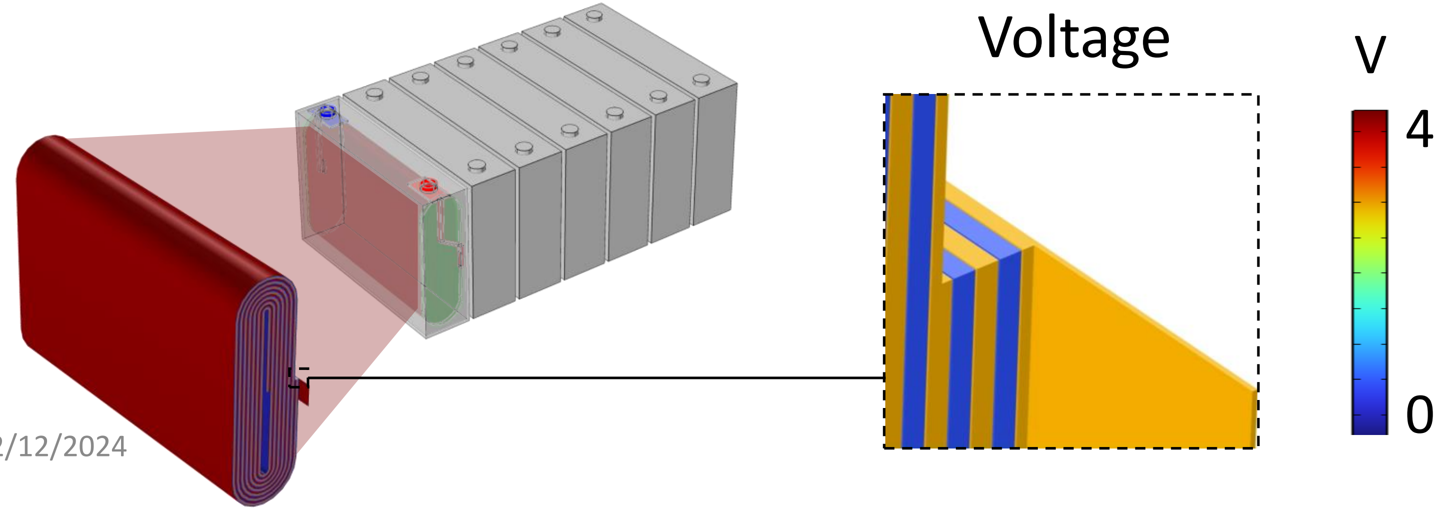


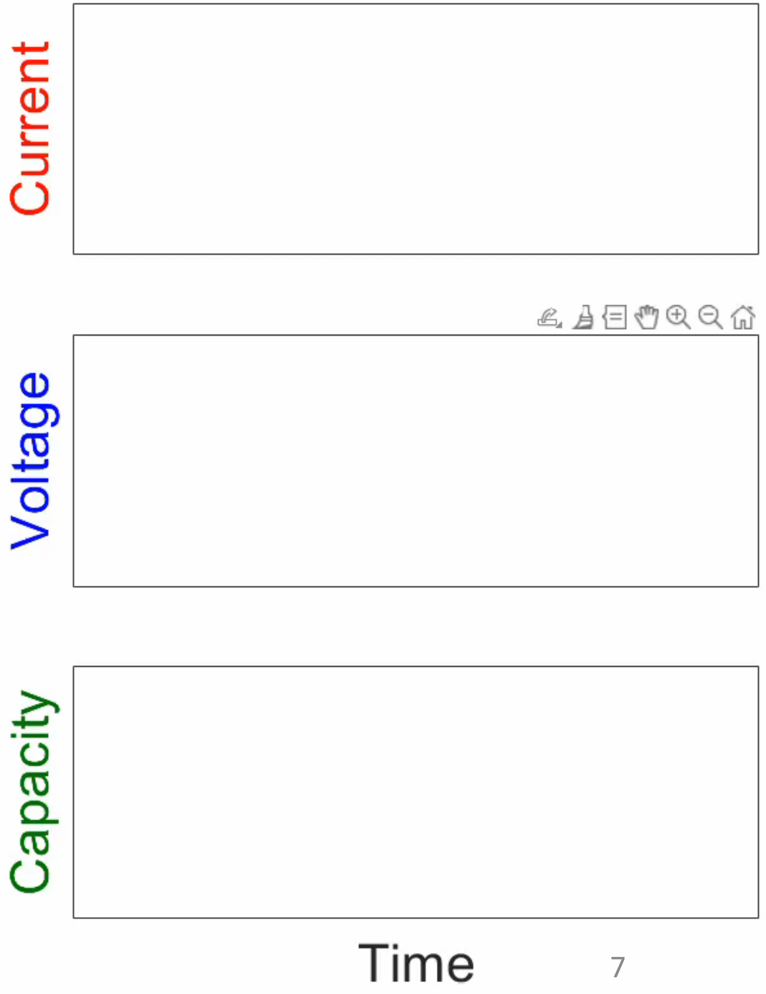
Thermal Management

Structural Durability

Simulating the Hybrid Pulse Power Characterization (HPPC) Test

- HPPC test = sequence of charge + discharge pulses to measure battery's life performance.
- Veryst simulated cell voltage response over 13 hours (simulation time << experimental time).





Direct Calculation of Voltage Losses

- Voltage loss is attributed to
  - **ohmic** resistances
  - **activation** of electrode kinetics
  - **concentration**-driven ion transport

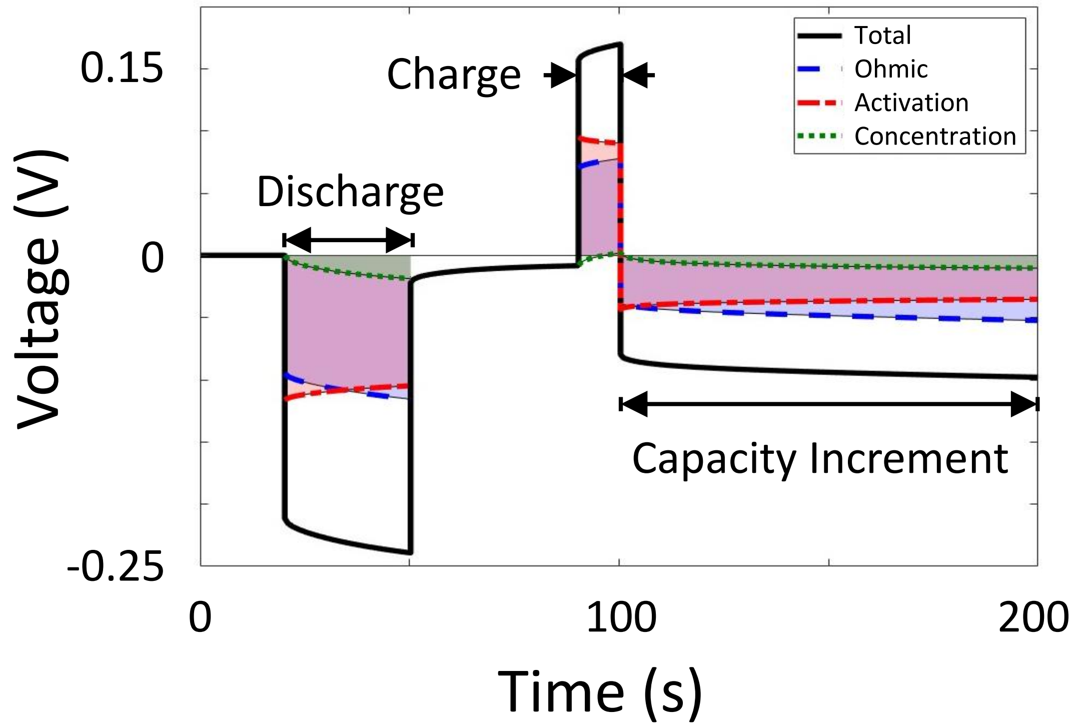
$$E_{\mathrm{loss}} = E_{\mathrm{ohm}} + E_{\mathrm{act}} + E_{\mathrm{conc}}$$

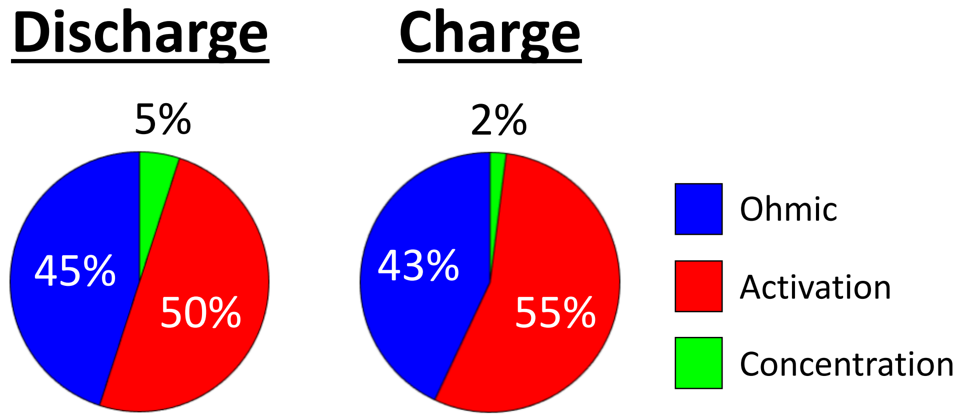
- Each loss term can be evaluated as COMSOL Variables, allowing direct measure of battery performance.

Variables

Name	Expression
E_l_neg	intop_neg(-phil_1dx*liion.Ilx)/i_cell
E_s_neg	intop_neg(-phis_1dx*liion.Isx)/i_cell
E_l_sep	intop_sep(-phil_1dx*liion.Ilx)/i_cell
E_l_pos	intop_pos(-phil_1dx*liion.Ilx)/i_cell
E_s_pos	intop_pos(-phis_1dx*liion.Isx)/i_cell
E_act_neg	intop_neg(liion.eta_per1*liion.iv_per1)/i_cell
E_act_pos	intop_pos(liion.eta_per1*liion.iv_per1)/i_cell
E_conc_particle_neg	intop_neg((liion.Eeq_per1-E_ocp_loc_neg)*liio
E_conc_electrode_neg	intop_neg((E_ocp_loc_neg-E_ocp_neg)*liion.iv
E_conc_neg	E_conc_electrode_neg+E_conc_particle_neg
E_conc_particle_pos	intop_pos((liion.Eeq_per1-E_ocp_loc_pos)*liio
E_conc_electrode_pos	intop_pos((E_ocp_loc_pos-E_ocp_pos)*liion.iv_
E_conc_pos	E_conc_electrode_pos+E_conc_particle_pos
E_neg	E_act_neg+E_l_neg+E_s_neg+E_conc_particle_
E_pos	E_act_pos+E_l_pos+E_s_pos+E_conc_particle_p

Results: Charge vs. Discharge Response





Activation polarization is the dominant source of loss.

Key factors that affect performance are electrode material selection, electrode microstructure, and electrolyte conductivity and stability.

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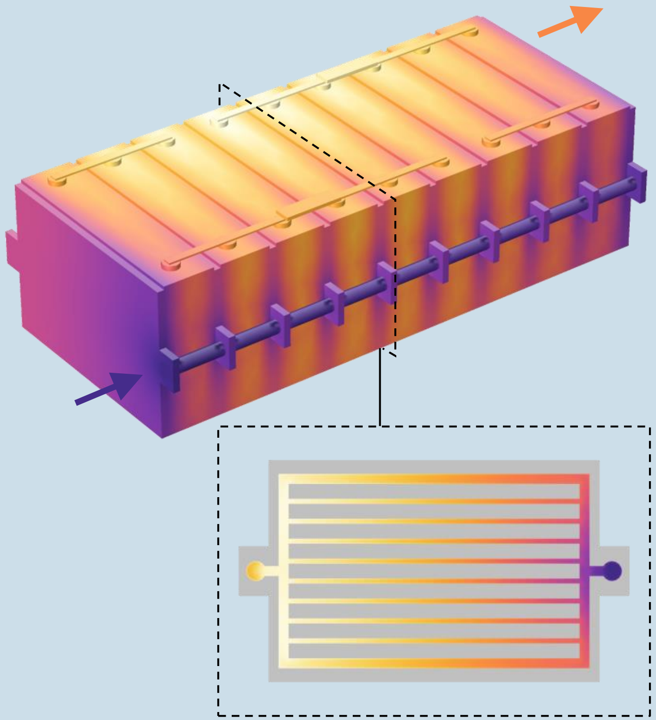
Lifetime Performance

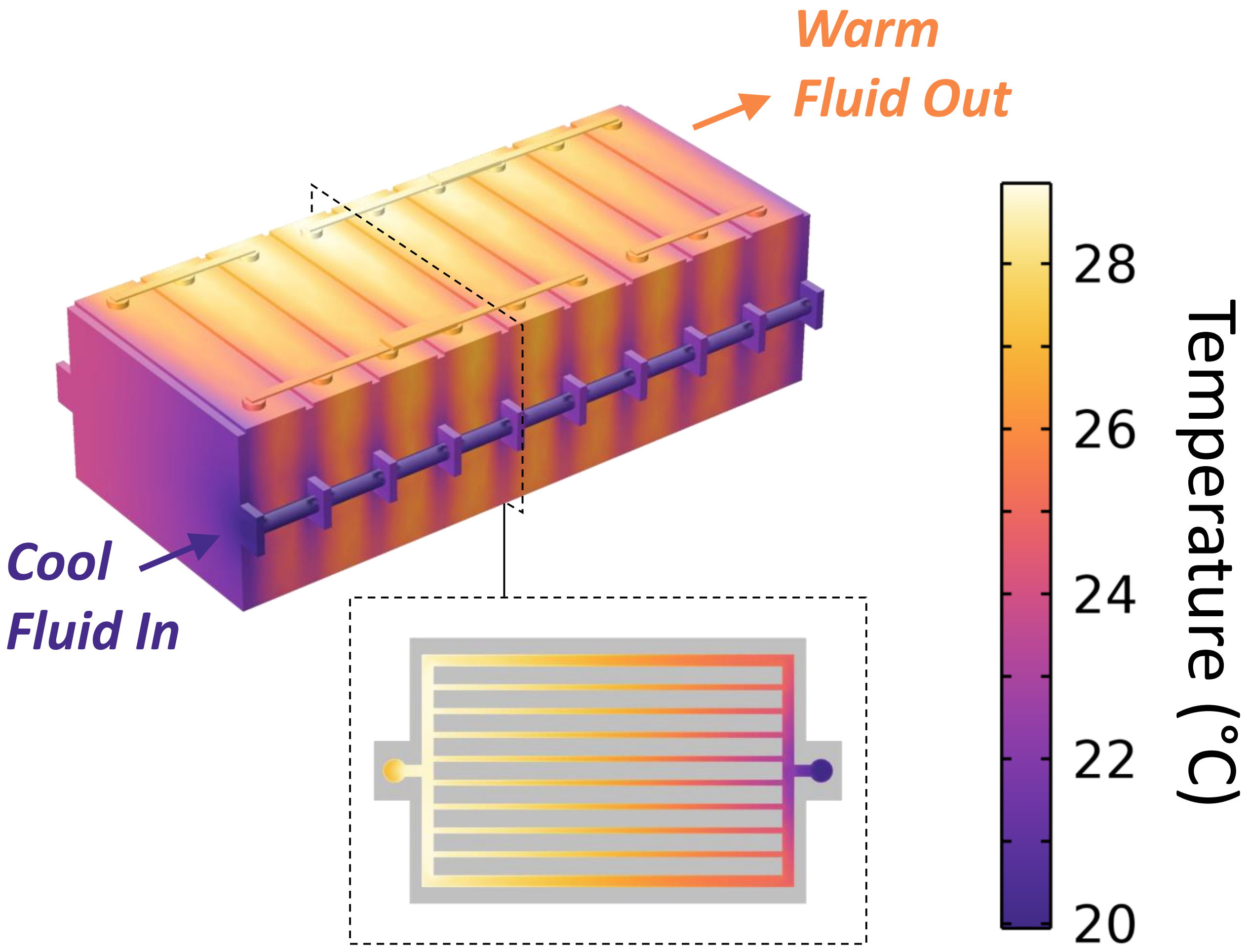
Thermal Management



Structural Durability

Simulating a Liquid-Cooled Battery Pack

- Batteries generate significant heat, require active cooling.
- Simulations can predict cooling rates to guide thermal design.
- Veryst simulated temperature distribution in a liquid-cooled battery pack to determine optimal coolant flow rates.

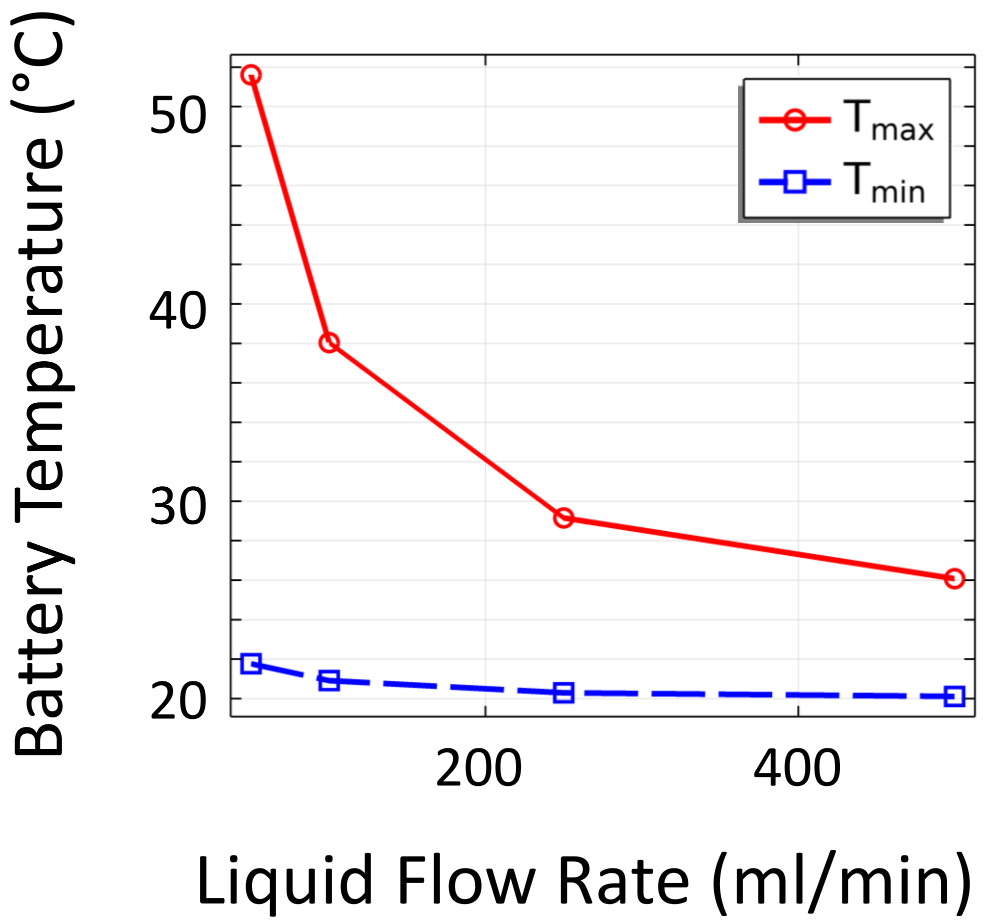


Results: Selecting Flow Rate to Achieve Target Battery Temperature

- Line plots of **maximum** and **minimum** temperature show higher flow improves uniformity.

- Flow rates > 500 ml/min required to maintain temperature < 26°C.

- Key factors that influence cooling:
  - Coolant selection & flow rate
  - Cooling plate selection
  - Thermal adhesive selection



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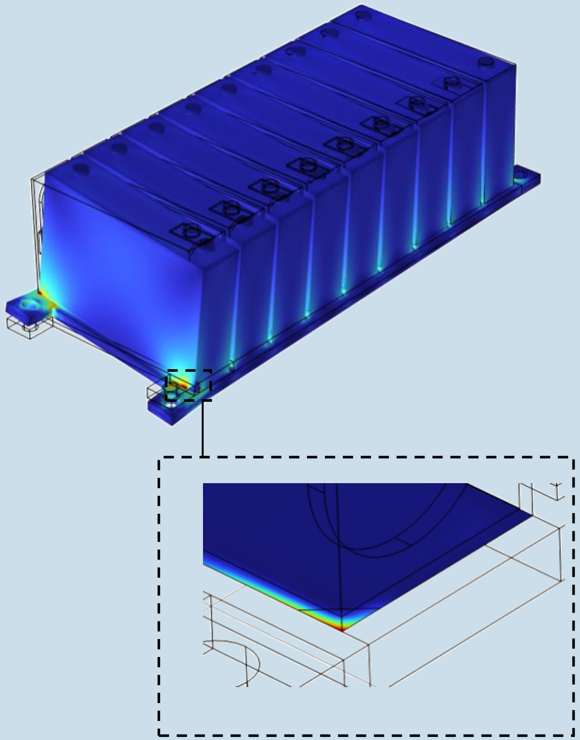
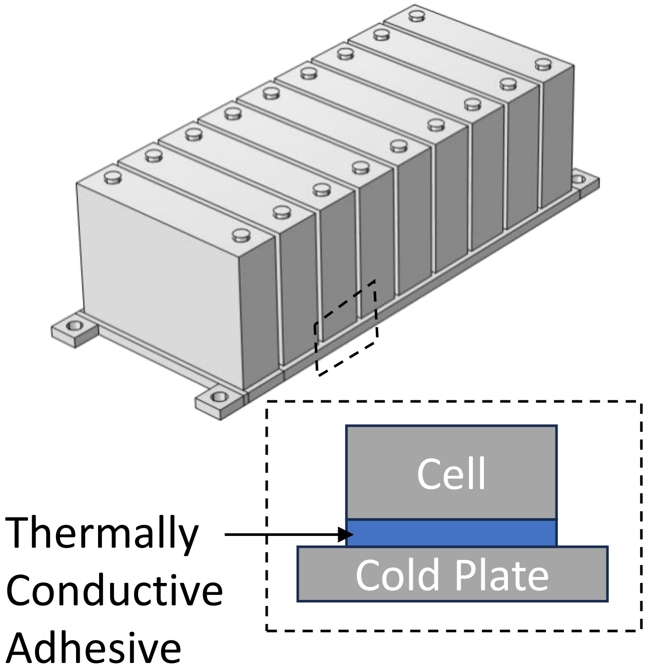
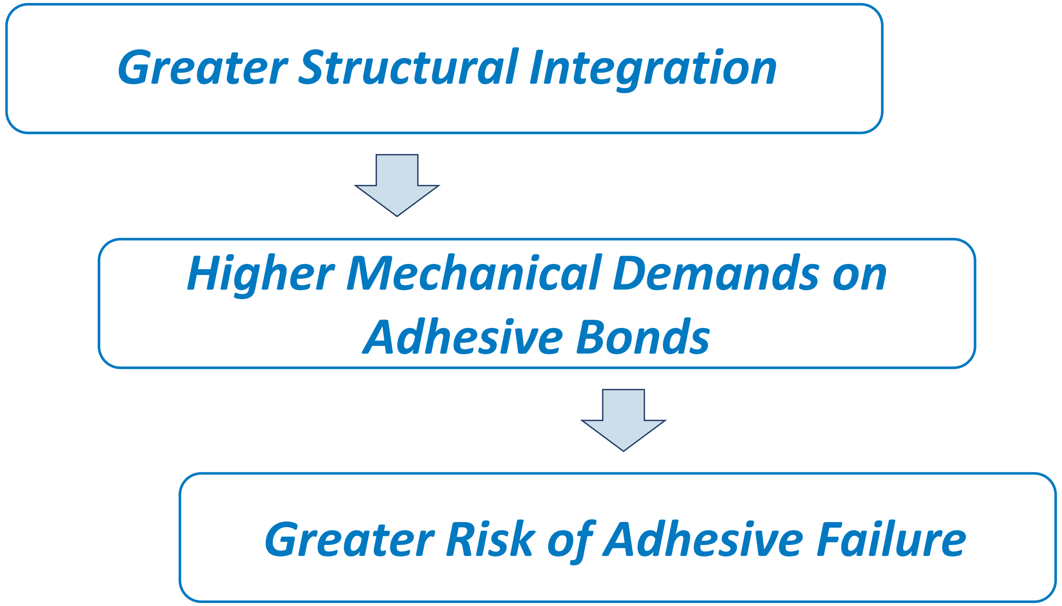


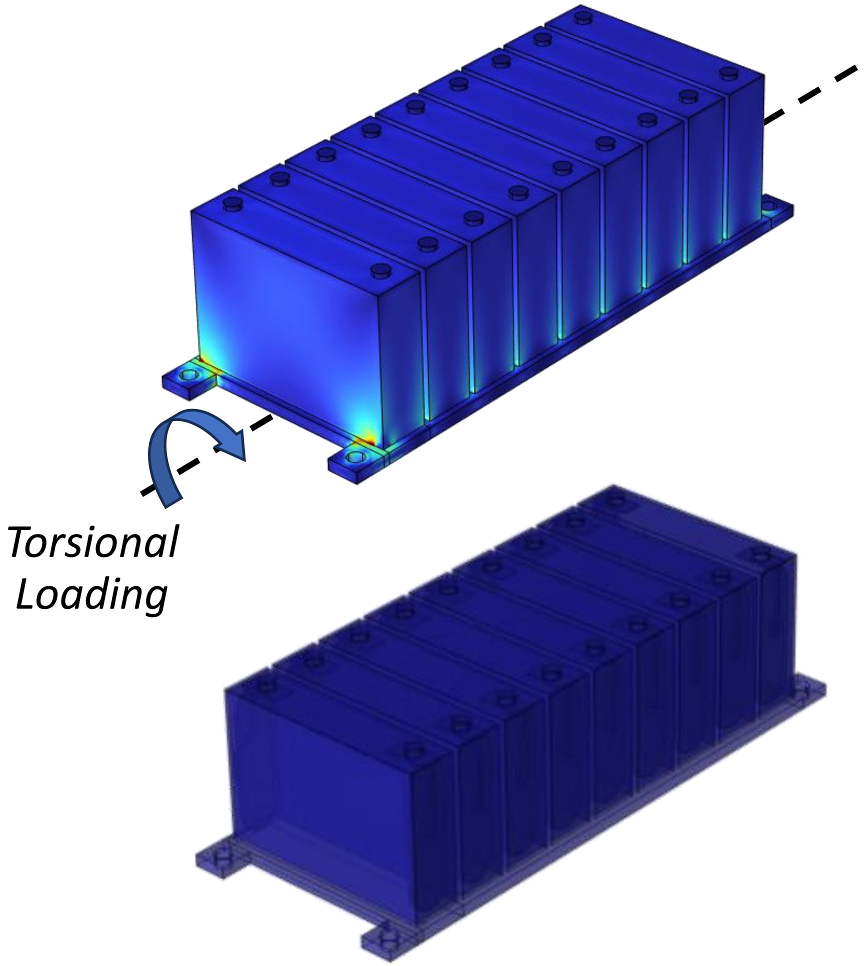
Simulating Adhesive Bonds in Packs

- Adhesives applications in batteries:
  - Cell-to-cell bonding
  - Cell-to-cold plate bonding
  - Sealed enclosures
- Veryst simulated adhesive stresses due to cyclic, torsional loading typically encountered during service.

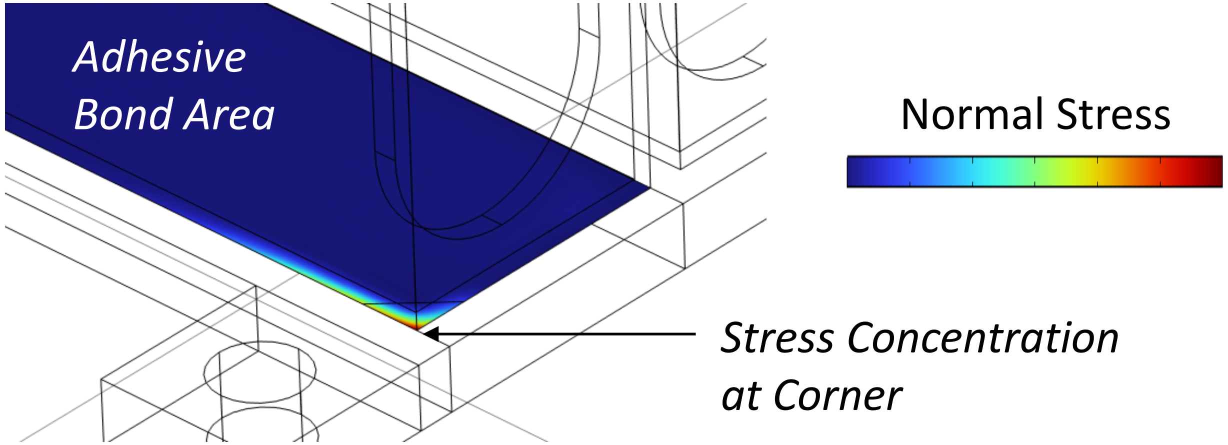


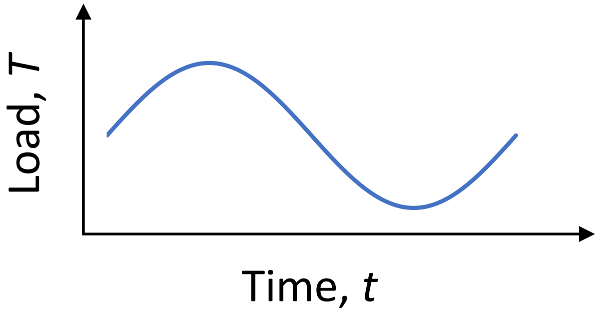


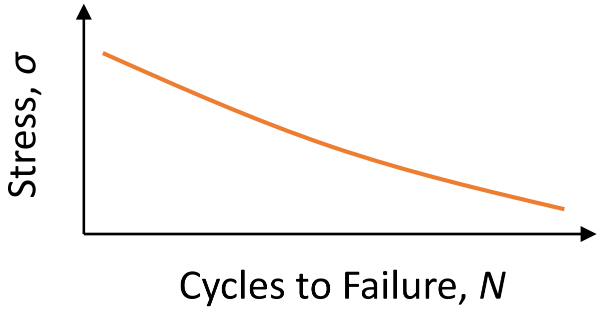
Results: Adhesive Stress Analysis



Stress analysis necessary to assess risk of fatigue debonding in cyclically loaded structures.







Conclusions

- Multiphysics simulation can help solve electrochemical, thermal, and mechanical problems for battery and automotive developers.

- In this presentation, Veryst used COMSOL Multiphysics® to predict…
  - internal resistances in a battery pack over range of useable capacity,
  - optimal coolant flow rates to maintain desired operating temperature,
  - adhesive stresses under cyclic loading that can lead to fatigue debonding.

- Simulations such as these can be used to inform battery design and operating parameters to optimize performance and life behavior.