MathWorks
AUTOMOTIVE CONFERENCE 2023
North America

Reduced Order Modeling for Battery Thermal Analysis

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Javier Gazzarri – Application Engineering, MathWorks

MathWorks

High Power

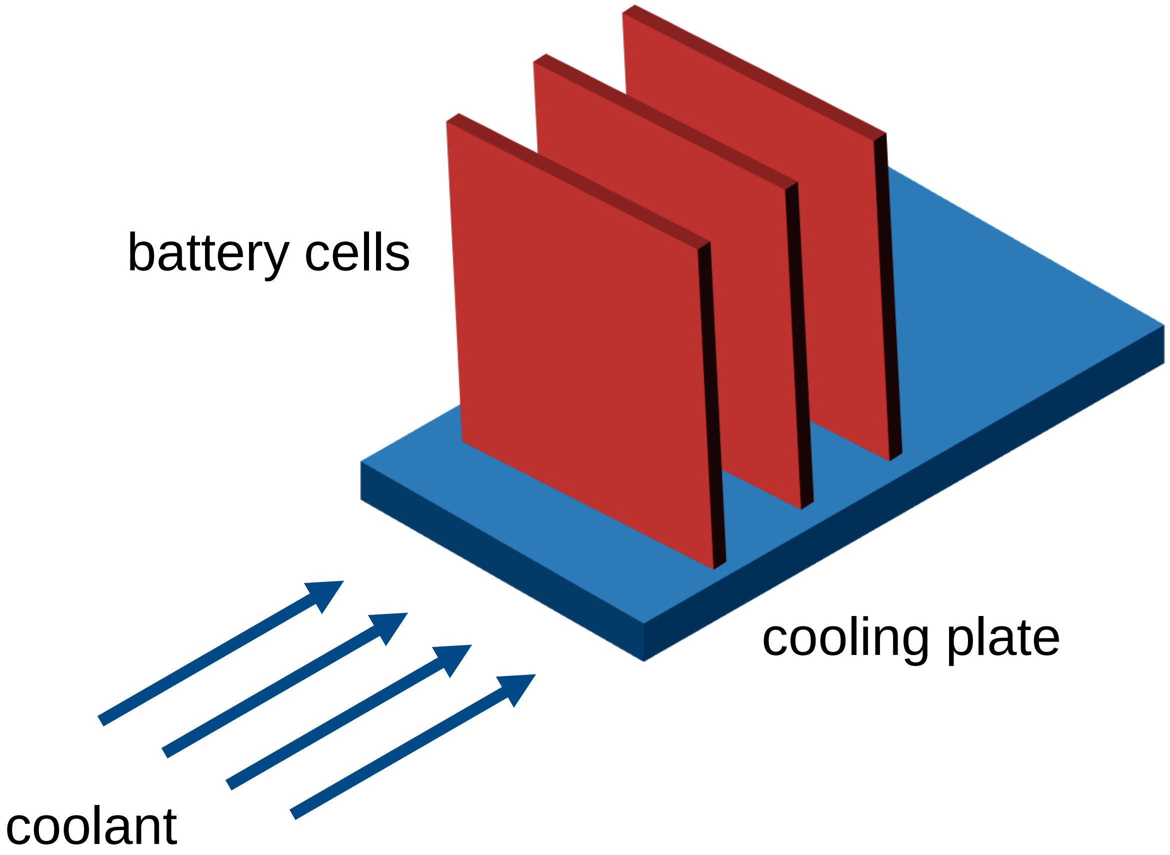
↓

High Heat Generation

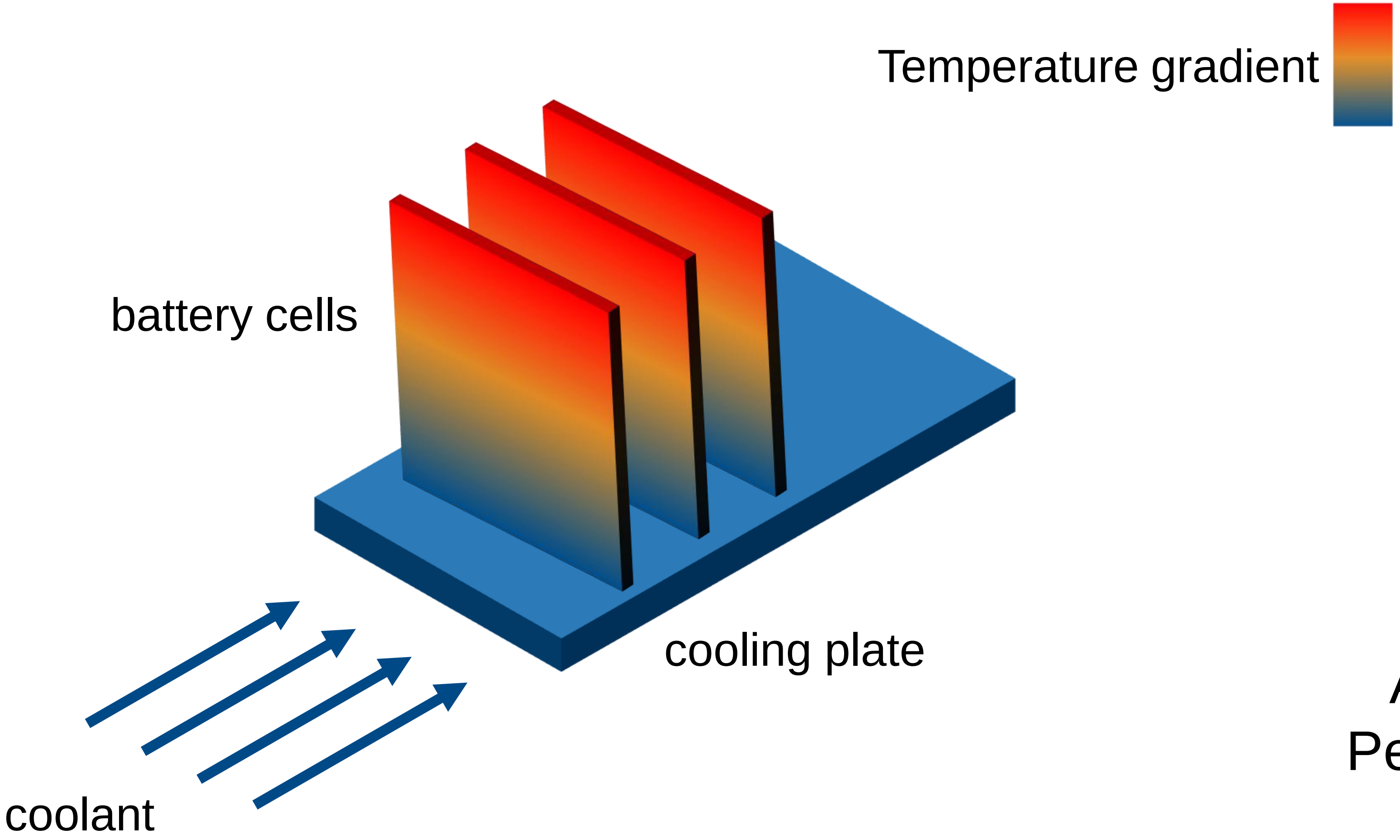
↓

Thermal Management

Pouch Cell with Bottom Plate Cooling



Pouch Cell with Bottom Plate Cooling



Aging Rate
Performance $= f\,(T)$

Temperature and Thermal Gradients in Battery Cells

Effects

- Heterogeneous resistance
- Uneven aging
- Localized heating
- Uncertain T monitoring

Requirements

Performance – Life – Safety

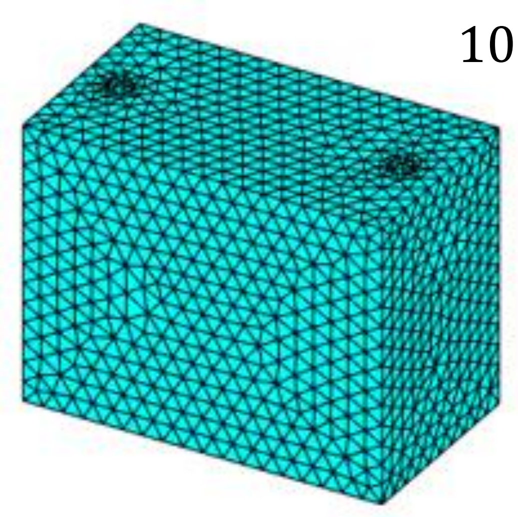
$$10^{o}C < T < 35^{o}C$$

$$\Delta T < 6^{o}C$$

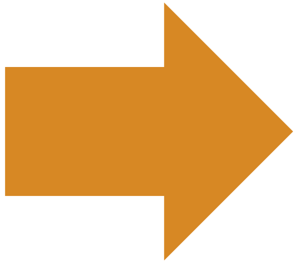
Modeling and Simulation

Requirements

- High fidelity
- Large model size



$10^3 \times 10^3 \sim 10^6 \times 10^6$

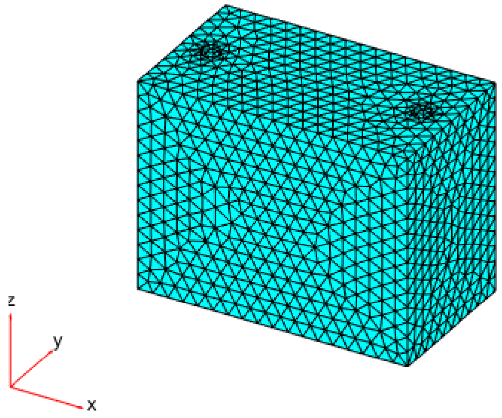


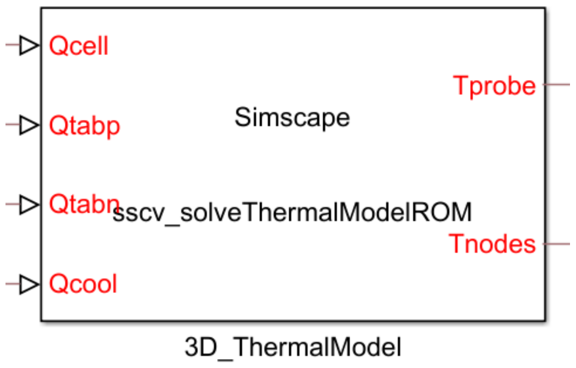
Effects

Slow

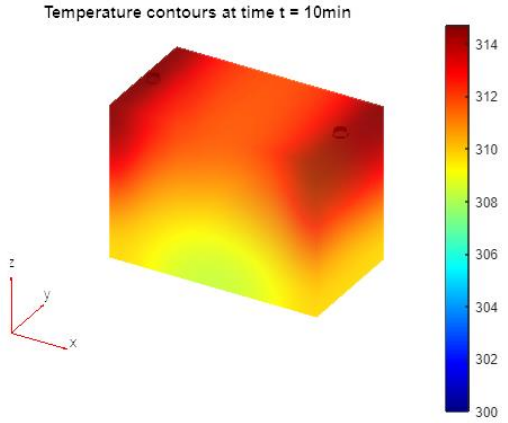
Agenda

- Reduced Order Model of Battery Thermal Behavior
- FEA to System Level



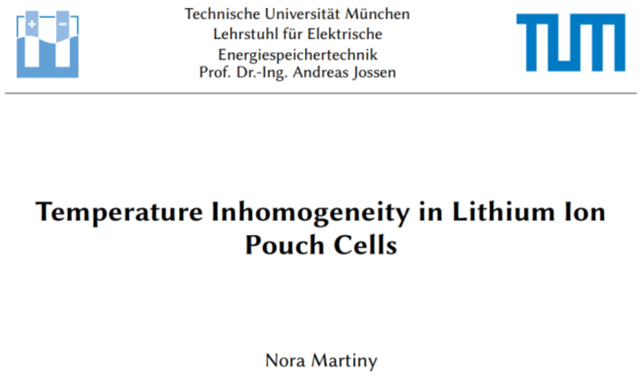


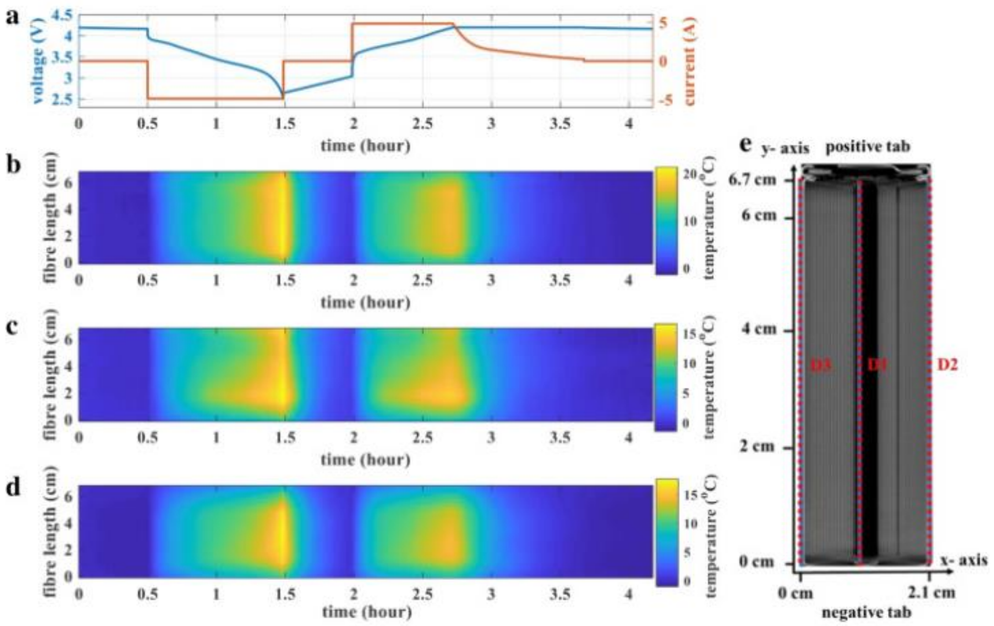
- Find Temperature Distribution
- Solve in Simulink



Battery Thermal Gradients - Research

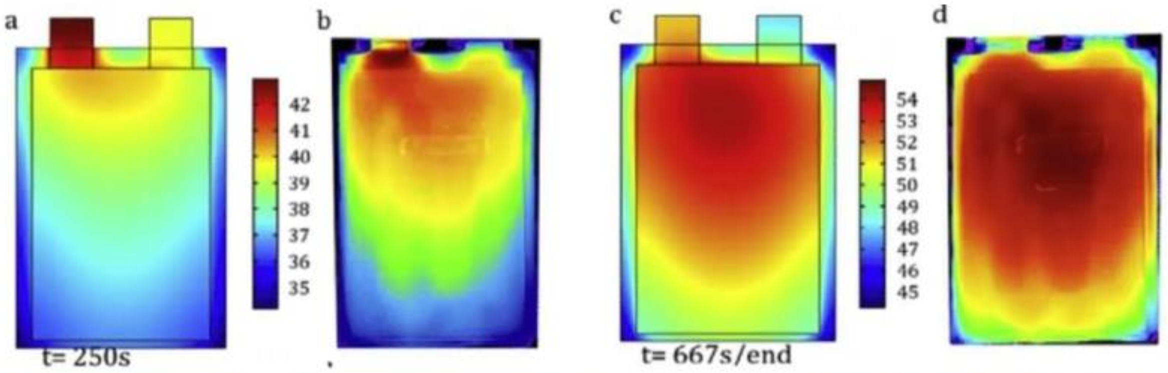
1388435.pdf (tum.de)





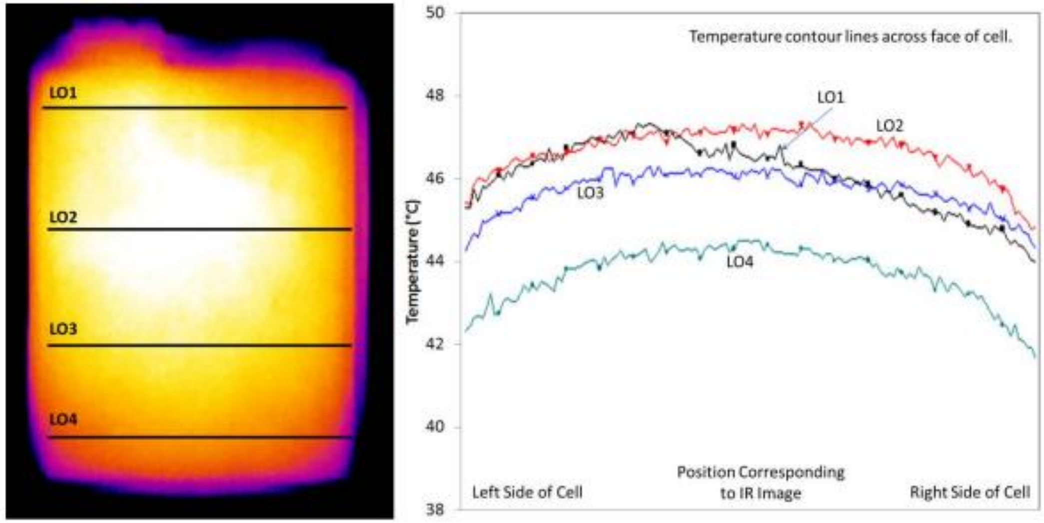
Yu et al., Distributed internal thermal monitoring of lithium ion batteries with fibre sensors - ScienceDirect

Enabling Fast Charging - Battery Thermal Considerations (osti.gov)



Surface temperature evolution of a pouch cell during 5C constant current discharge obtained by a) simulation and b) measurement at t ¼ 250 s; c) simulation and d) measurement at the end of discharge/t ¼ 667 s

S. Goutam et al. 10.1016/J.APPLTHERMALENG.2017.07.206
https://www.sciencedirect.com/science/article/pii/S1359431117325565?via{%}3Dihub



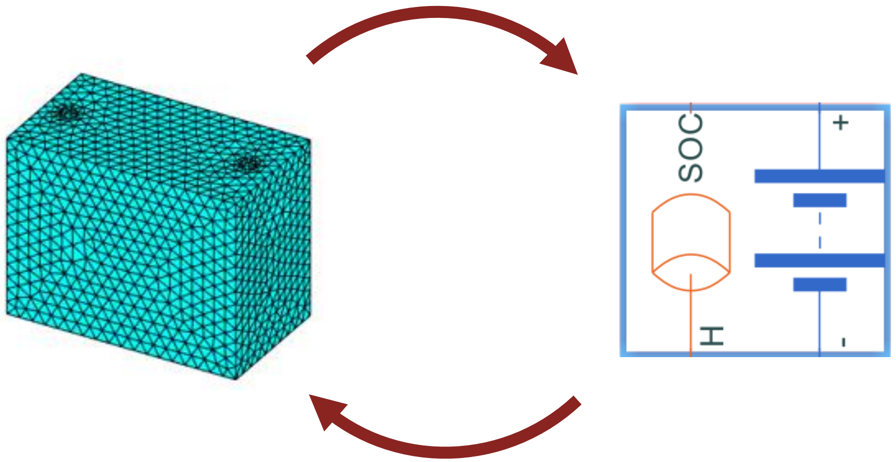
NMC/graphite, End of a 2C constant current discharge. SOC 100% to 0%

Solution

Finite Element Analysis + System Level Simulation

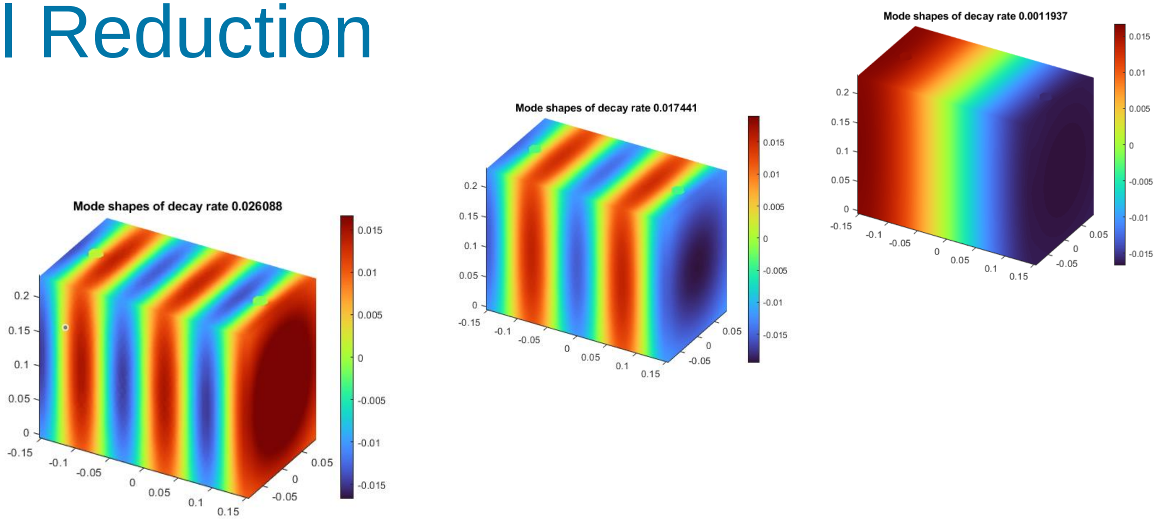
- Thermal Domain - Reduced Order Model from FEA - **PDE Toolbox**

- Electrical Domain - Battery Cell - **Simscape Battery**



Model Reduction PDE Toolbox

Thermal Problem Model Reduction



Modes Φ_r

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot \mathrm{k} \nabla T = q$$

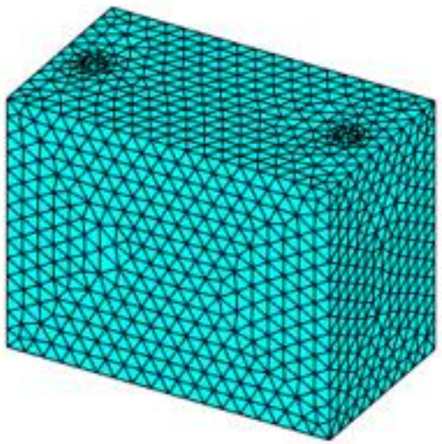
FEM

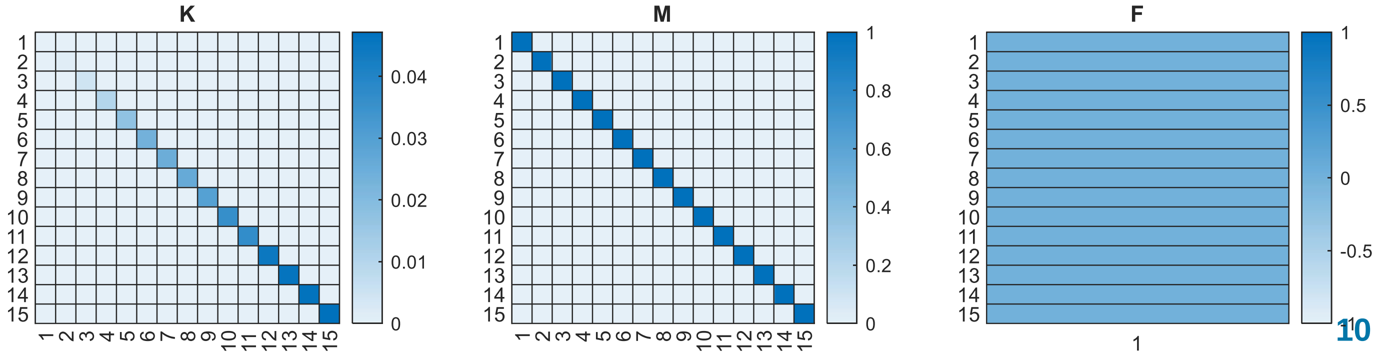
$$M\dot{T} + KT = Q$$

Reduction

$$M_r = \Phi_r^T M \Phi_r$$

$$M_r \dot{T}_r + K_r T_r = Q_r$$





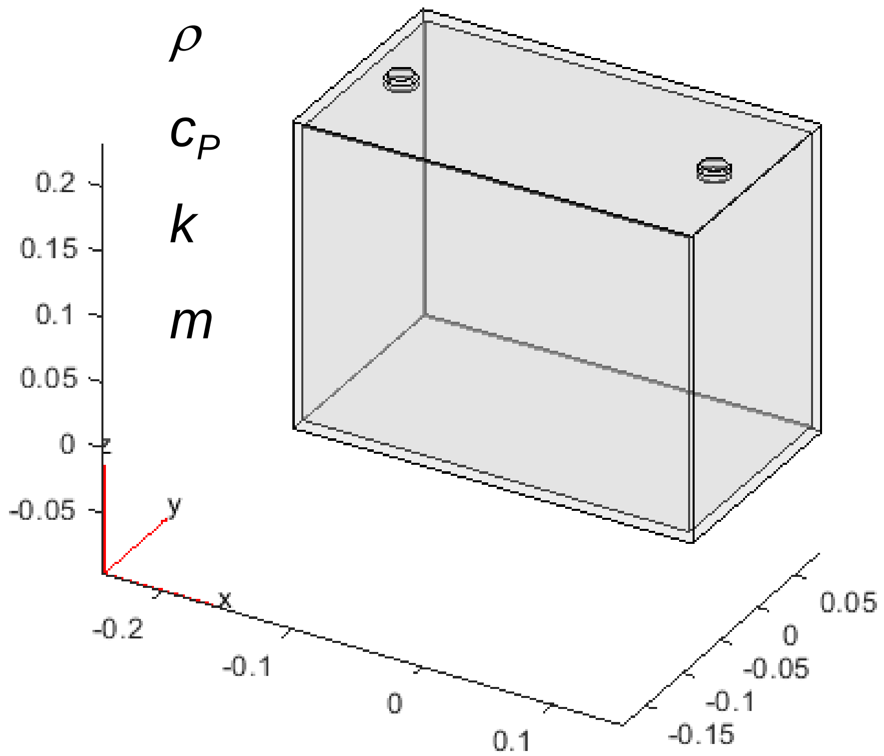
SAND2010-6352 (osti.gov)

Thermal Model Reduction - Workflow

1- Create geometry

2- Create thermal problem as `‘modal’`

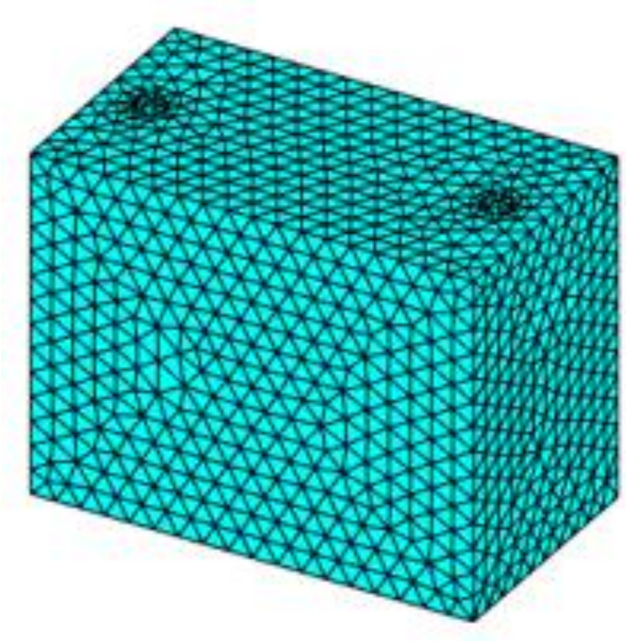
3- Assign material properties




```
model = createpde('thermal','modal');
```

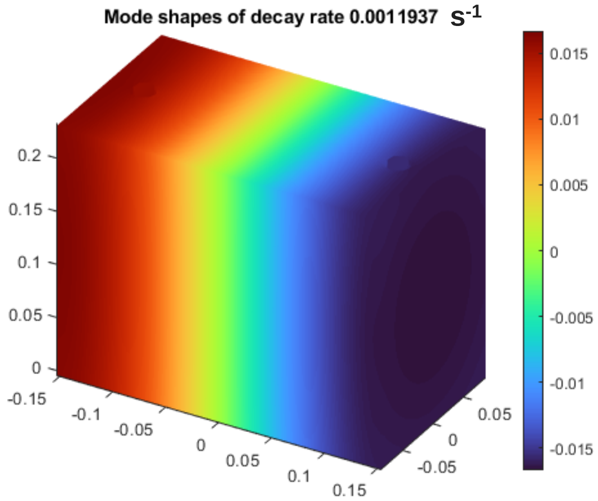
Thermal Model Reduction - Workflow

4- Mesh



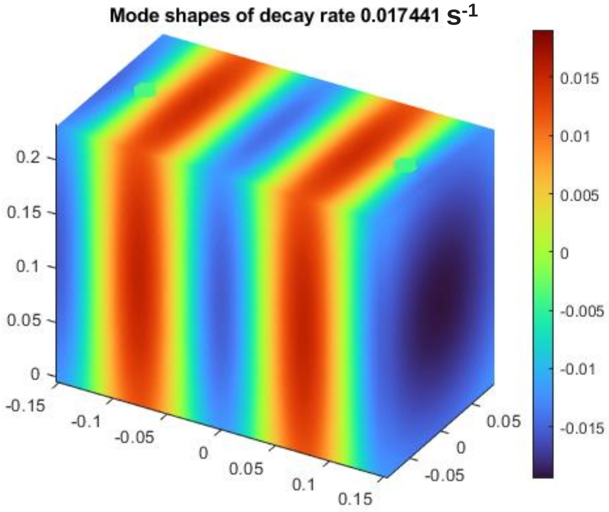
```
model.generateMesh('Hface',
{model.Geometry.cellFaces(1),0.03});
```

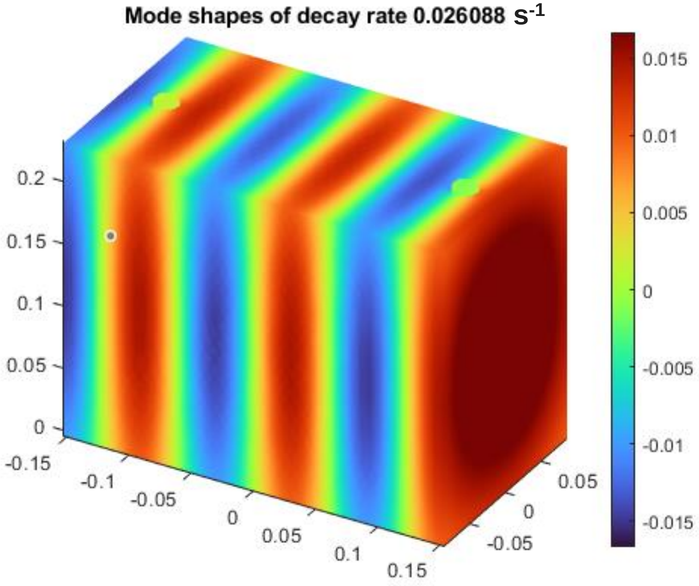
Thermal Model Reduction - Workflow



5- Solve modal problem (no loads)

```
Rm = solve(model,'DecayRange',[-inf,0.05]);
```





Thermal Model Reduction - Workflow

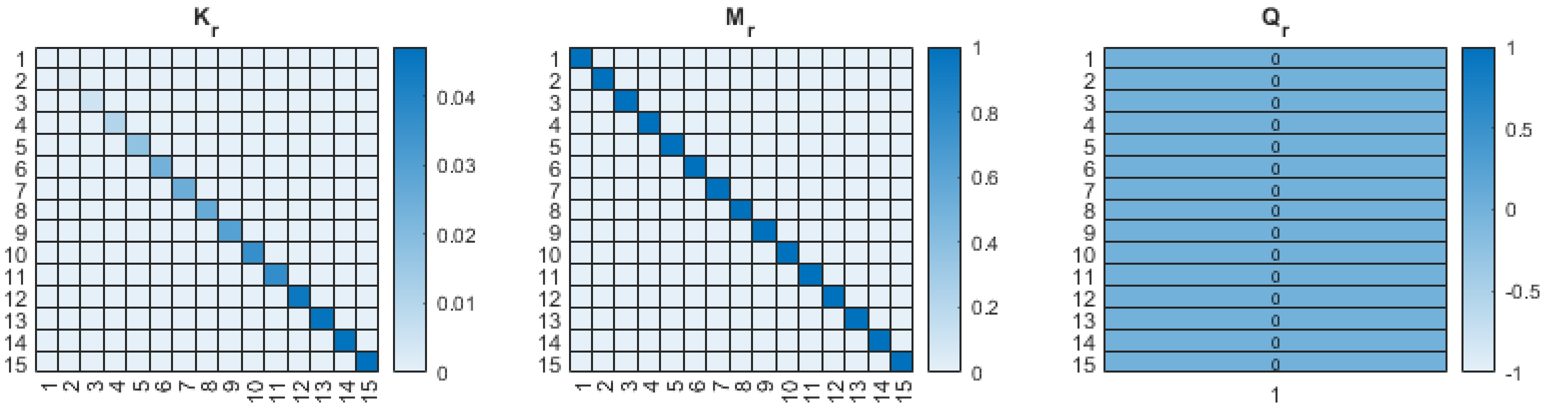
6- Reduce

```
rom = reduce(model,'ModalResults',Rm);
```

$$\text{Rm} \in 15{,}684 \times 15$$

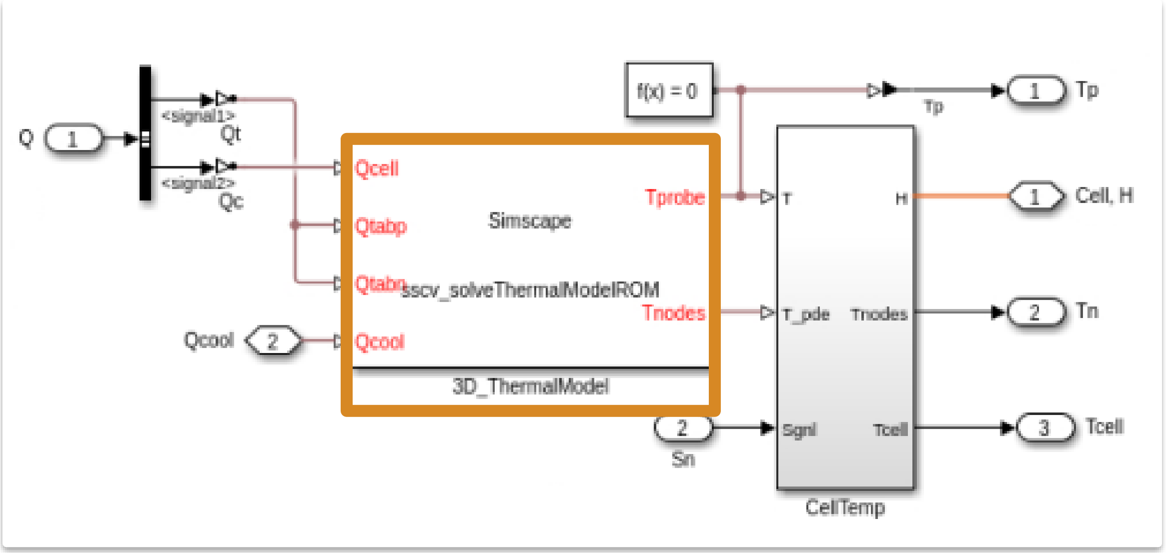
`rom`

$$M_r\dot{T}_r + K_rT_r = Q_r$$



System-Level Model
Simscape

Reduced Order Model in Simscape Language



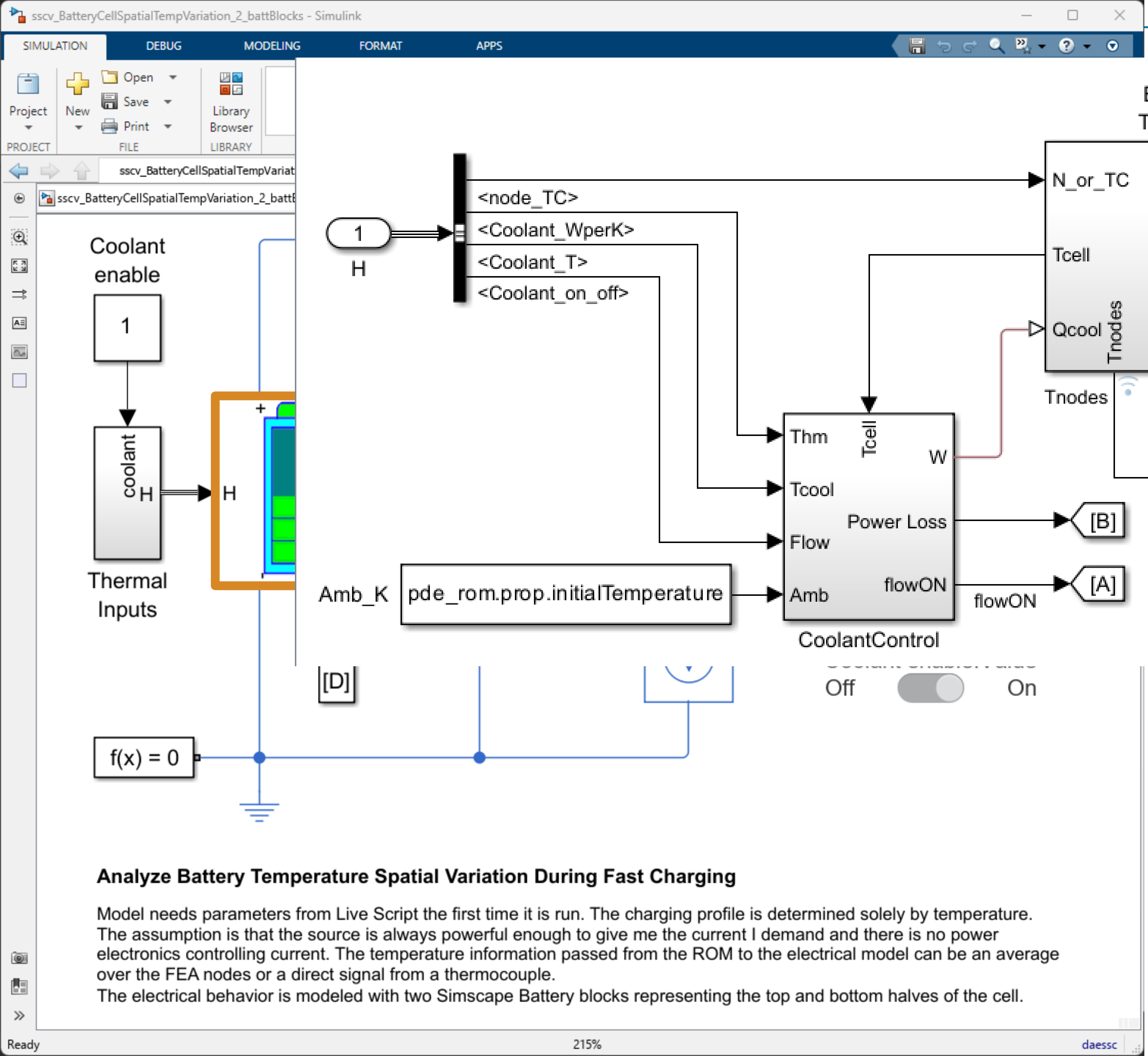

```
component sscv_solveThermalModelROM
% Reduced Order Model matrices and operations for battery cell thermal analysis

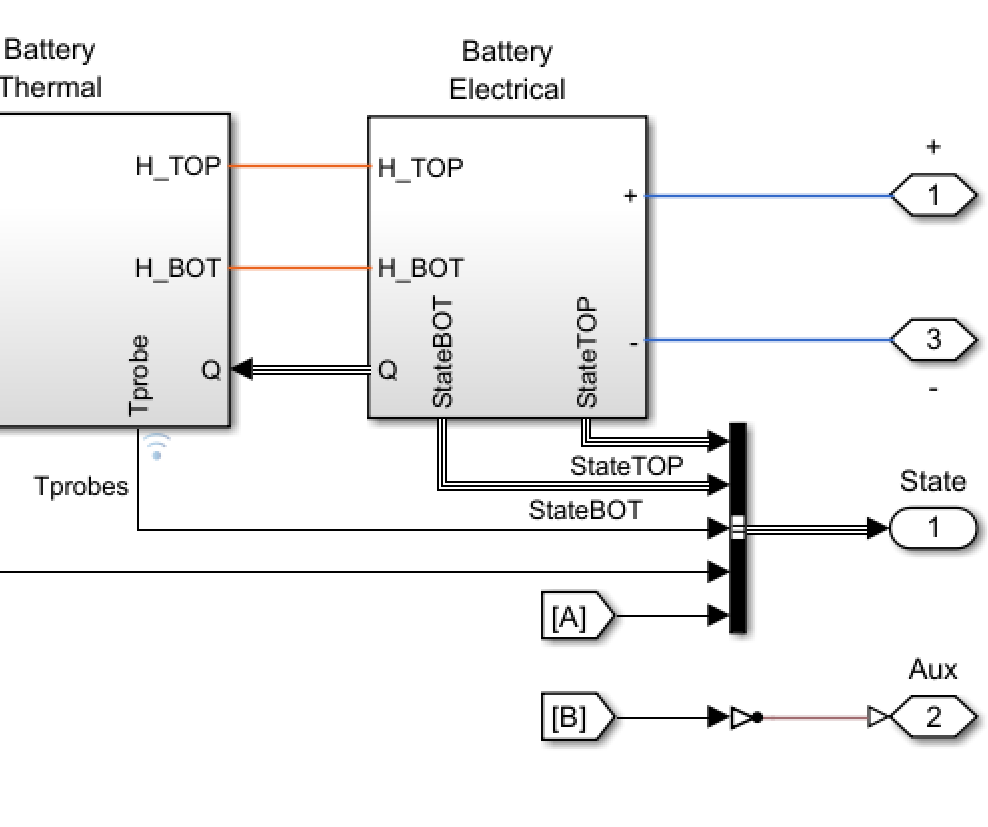
% Copyright 2022 The MathWorks, Inc.
```

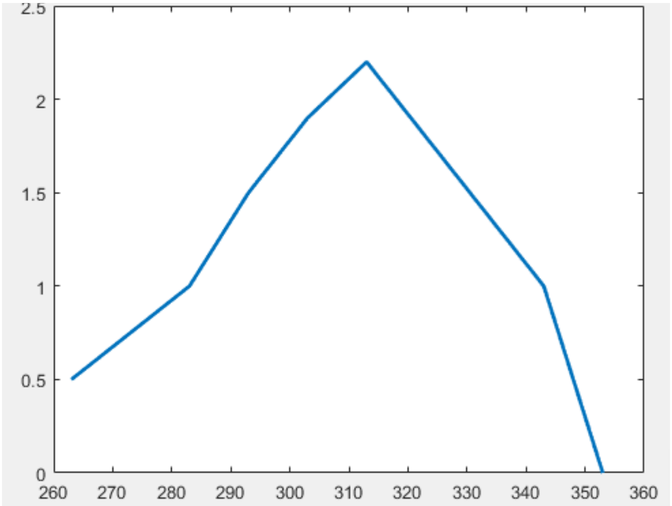
```
equations
    pdeTemp == T;
    romTemp == probeTransformMat*T;
    romMassMatrix * T.der  + romCondMatrix * T == {romQmodalTransform'*(...
        romQheatGenUnitFull*value(cellHeatSrc,'W')/jellyVolume + ...
        romQheatGenUnitPosTabFull*value(tabHeatSrcPos,'W')/posTabVolume + ...
        romQheatGenUnitNegTabFull*value(tabHeatSrcNeg,'W')/negTabVolume + ...
        romQboundaryLoadFull*value(heatLossToCoolant,'W')/coolingSurfArea...
        ),'W'};
```

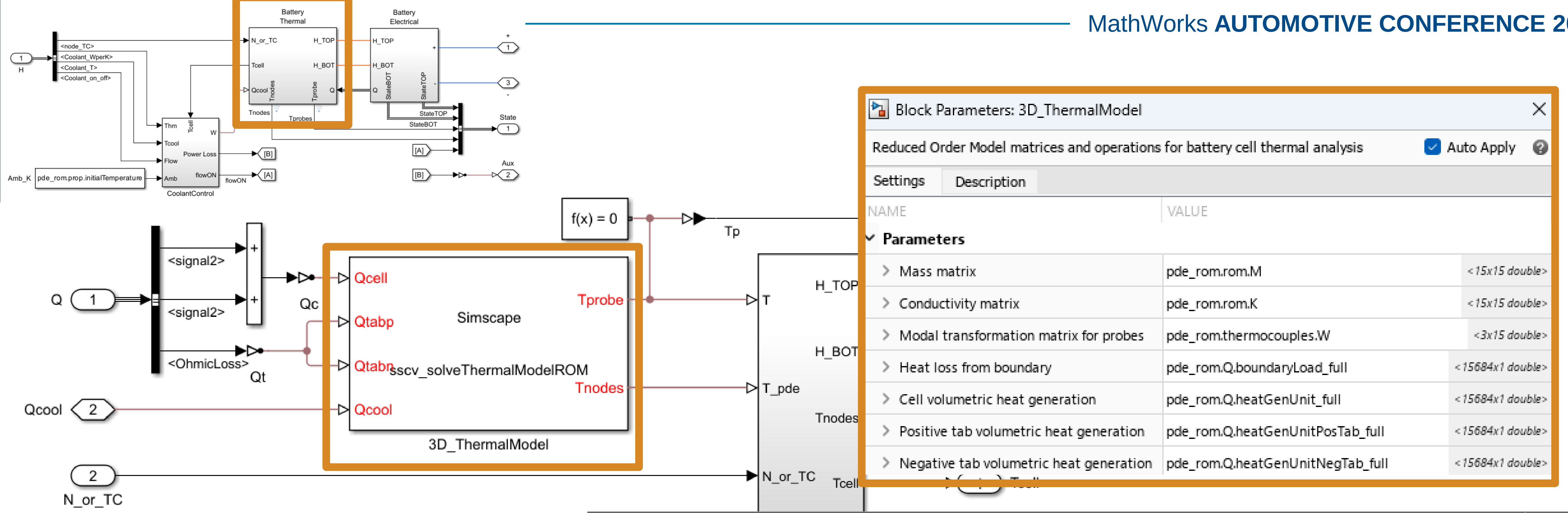
$$M_r\dot{T}_r + K_r T_r = Q_r$$

model


sscv_BatteryCellSpatialTempVariation_2_battBlocks - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
APPS
Project
New
Open
Save
Print
Library Browser
PROJECT
FILE
LIBRARY
Coolant enable
Thermal Inputs
f(x) = 0
[D]
Off
On
Analyze Battery Temperature Spatial Variation During Fast Charging
Model needs parameters from Live Script the first time it is run. The charging profile is determined solely by temperature. The assumption is that the source is always powerful enough to give me the current I demand and there is no power electronics controlling current. The temperature information passed from the ROM to the electrical model can be an average over the FEA nodes or a direct signal from a thermocouple.
The electrical behavior is modeled with two Simscape Battery blocks representing the top and bottom halves of the cell.
Ready
215%
daessc


Battery Thermal
Battery Electrical
<node_TC>
<Coolant_WperK>
<Coolant_T>
<Coolant_on_off>
H
N_or_TC
Tcell
Qcool
Tnodes
Tprobe
H_TOP
H_BOT
Q
StateBOT
StateTOP
Tnodes
Tprobes
Thm
Tcool
Flow
Amb
W
Power Loss
flowON
CoolantControl
Amb_K
pde_rom.prop.initialTemperature
[B]
[A]
State
Aux


2.5
2
1.5
1
0.5
0
260
270
280
290
300
310
320
330
340
350
360



The battery cell block and the custom ROM block exchange information via the
port H (acausal) and the heat loss term Q (signal from battery block). The batter
calculate Q and Q is used as a heat source for the thermal ROM.

```
component sscv_solveThermalModelROM
% Reduced Order Model matrices and operations for battery cell thermal analysis

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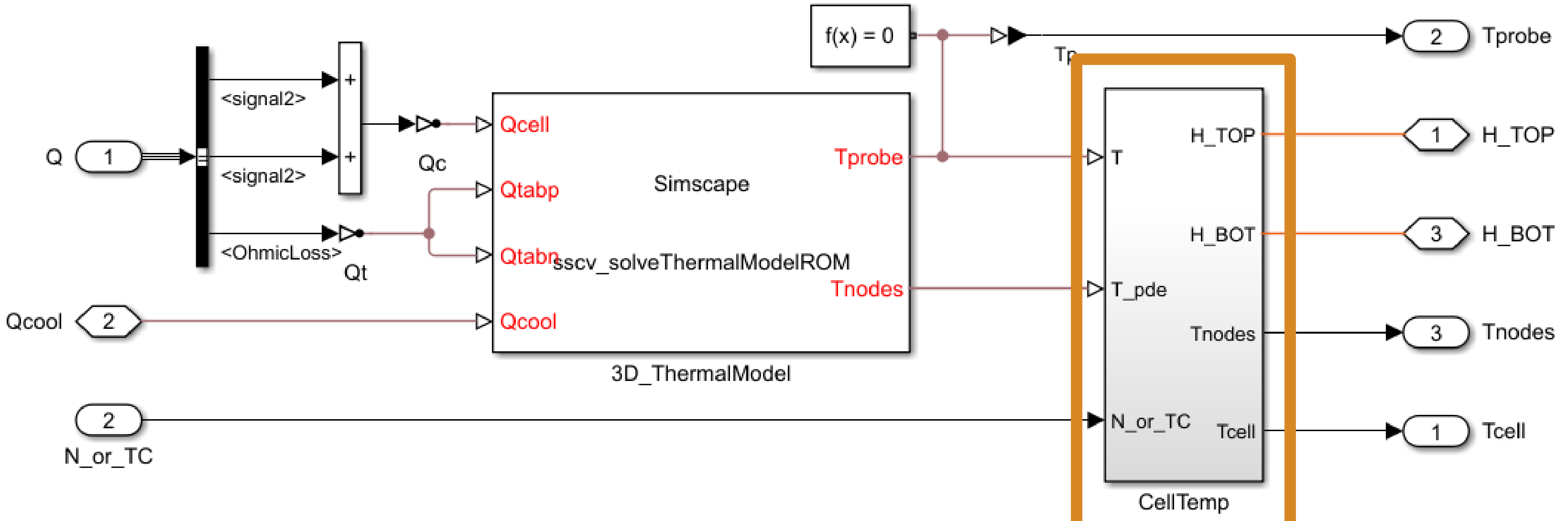
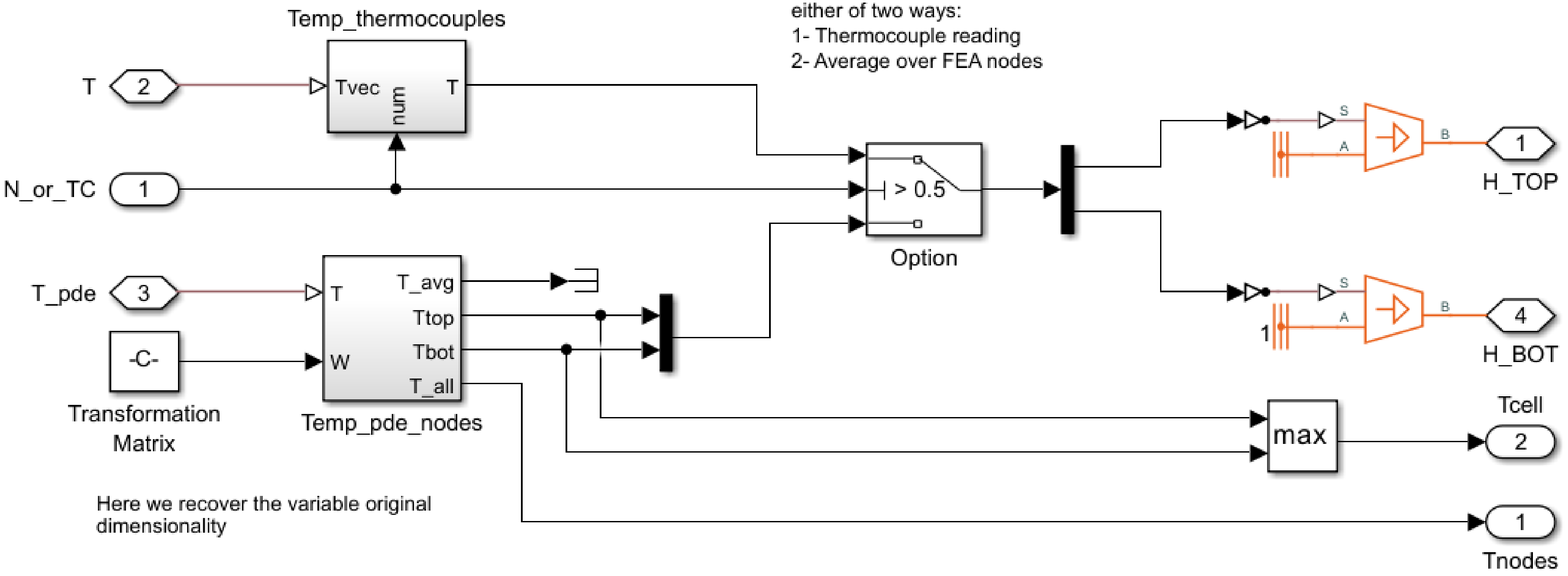
$$M_r \dot{T}_r + K_r T_r = Q_r$$

```
equations
    pdeTemp == T;
    romTemp == probeTransformMat*T;
    romMassMatrix * T.der  + romCondMatrix * T == {romQmodalTransform'*(...
        romQheatGenUnitFull*value(cellHeatSrc,'W')/jellyVolume + ...
        romQheatGenUnitPosTabFull*value(tabHeatSrcPos,'W')/posTabVolume + ...
        romQheatGenUnitNegTabFull*value(tabHeatSrcNeg,'W')/negTabVolume + ...
        romQboundaryLoadFull*value(heatLossToCoolant,'W')/coolingSurfArea...
        ),'W'};
```

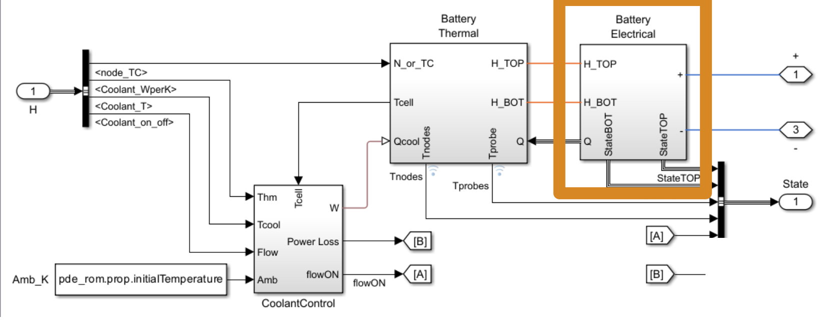


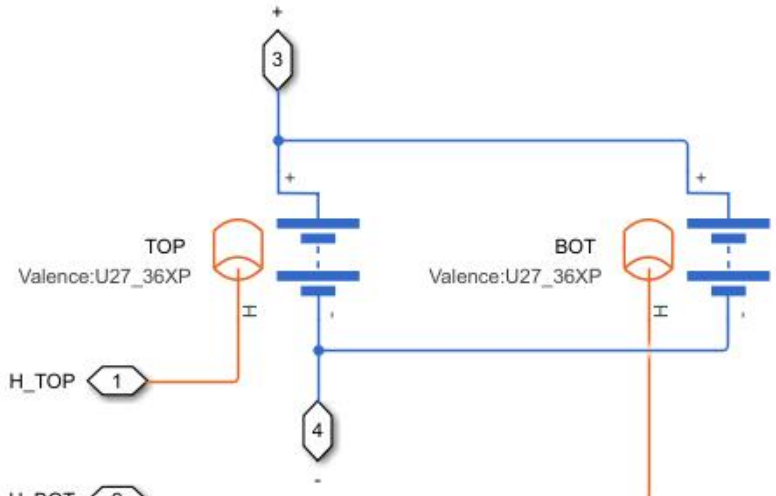
The battery cell block and the custom ROM block exchange information via the thermal port H (acausal) and the heat loss term Q (signal from battery block). The battery blocks calculate Q and Q is used as a heat source for the thermal ROM.

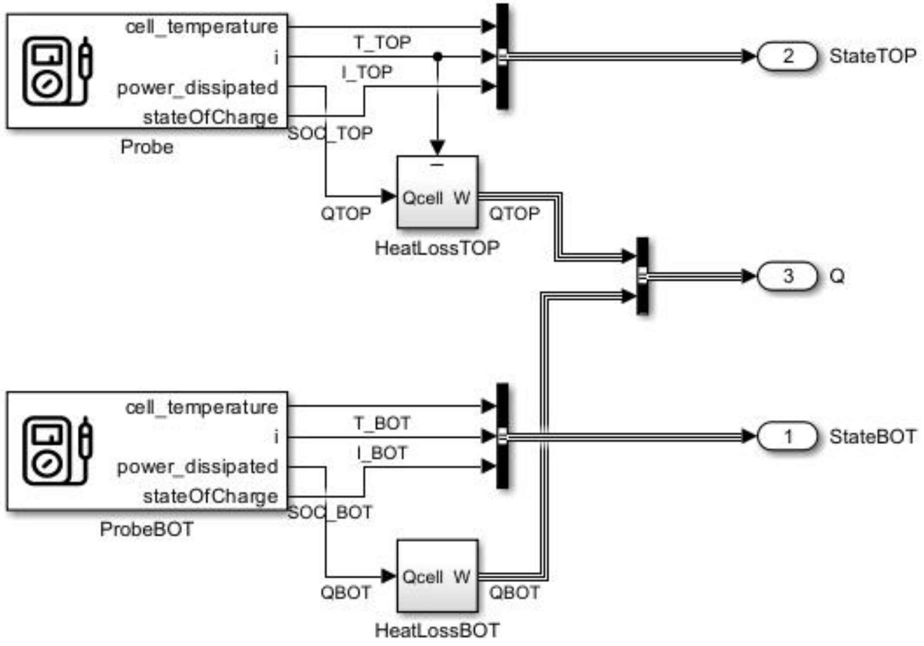
The temperature distribution calculated with the ROM is passed to Simscape in either of two ways:
1- Thermocouple reading
2- Average over FEA nodes

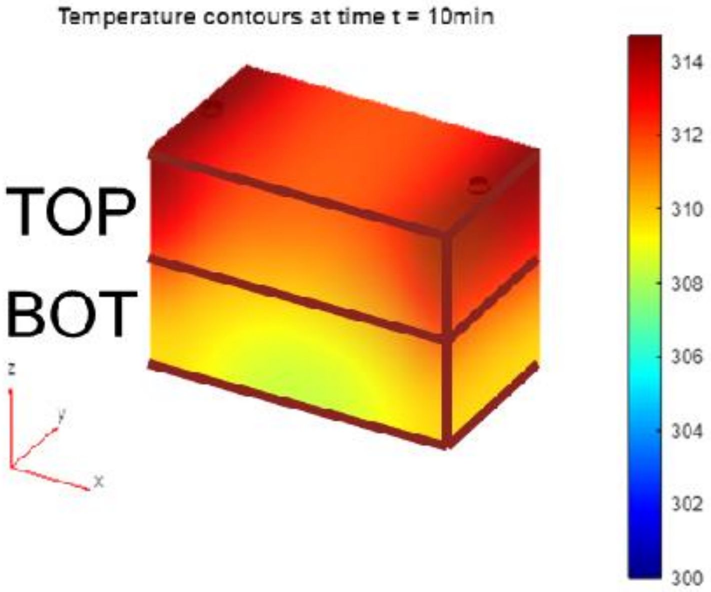


Here we recover the variable original dimensionality







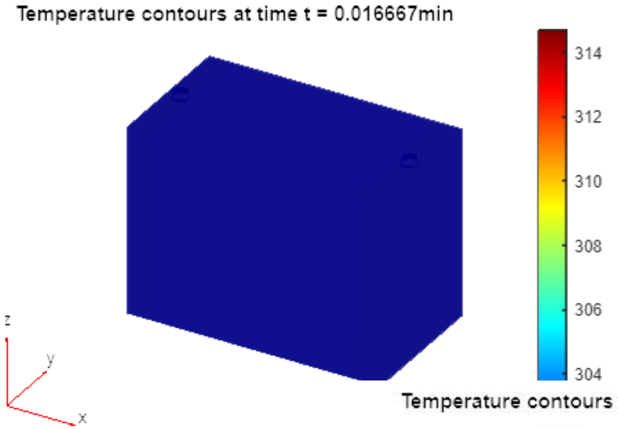


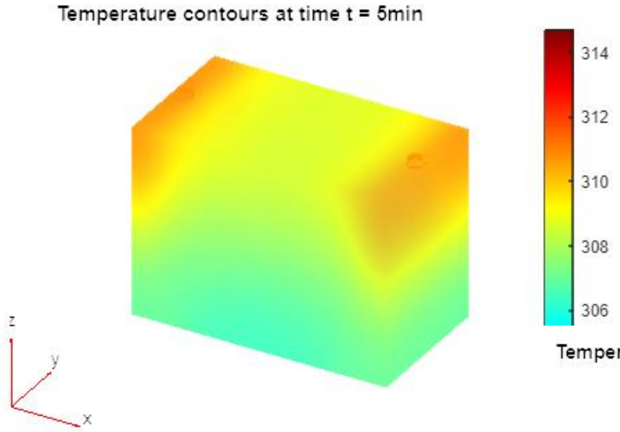
The electrical behavior is modeled with two Simscape Battery blocks in parallel, representing the top and bottom half of the battery cell. Parameterization for each of them is modified to represent half a cell each: 2 x Resistance, 0.5 x Capacity, 0.5 x Thermal Mass. Their thermal ports are connected to the ROM model which receives the heat Q as input and uses it as a source. Q is the sum of the heat dissipated in the battery cell (both blocks) and the ohmic losses in the bus bars (top half).

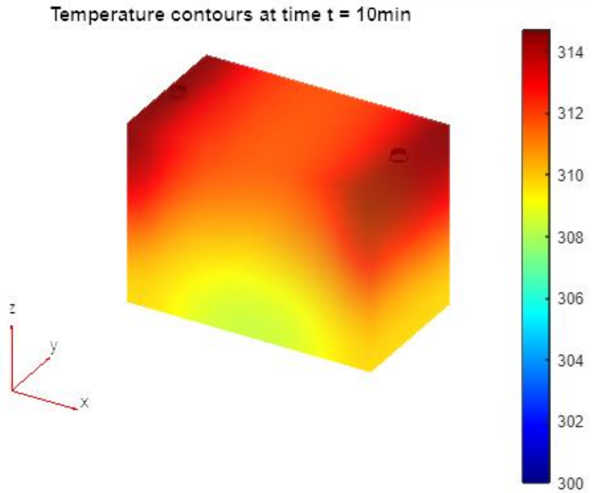
The predominantly vertical direction temperature gradient justifies the top and bottom half partition.

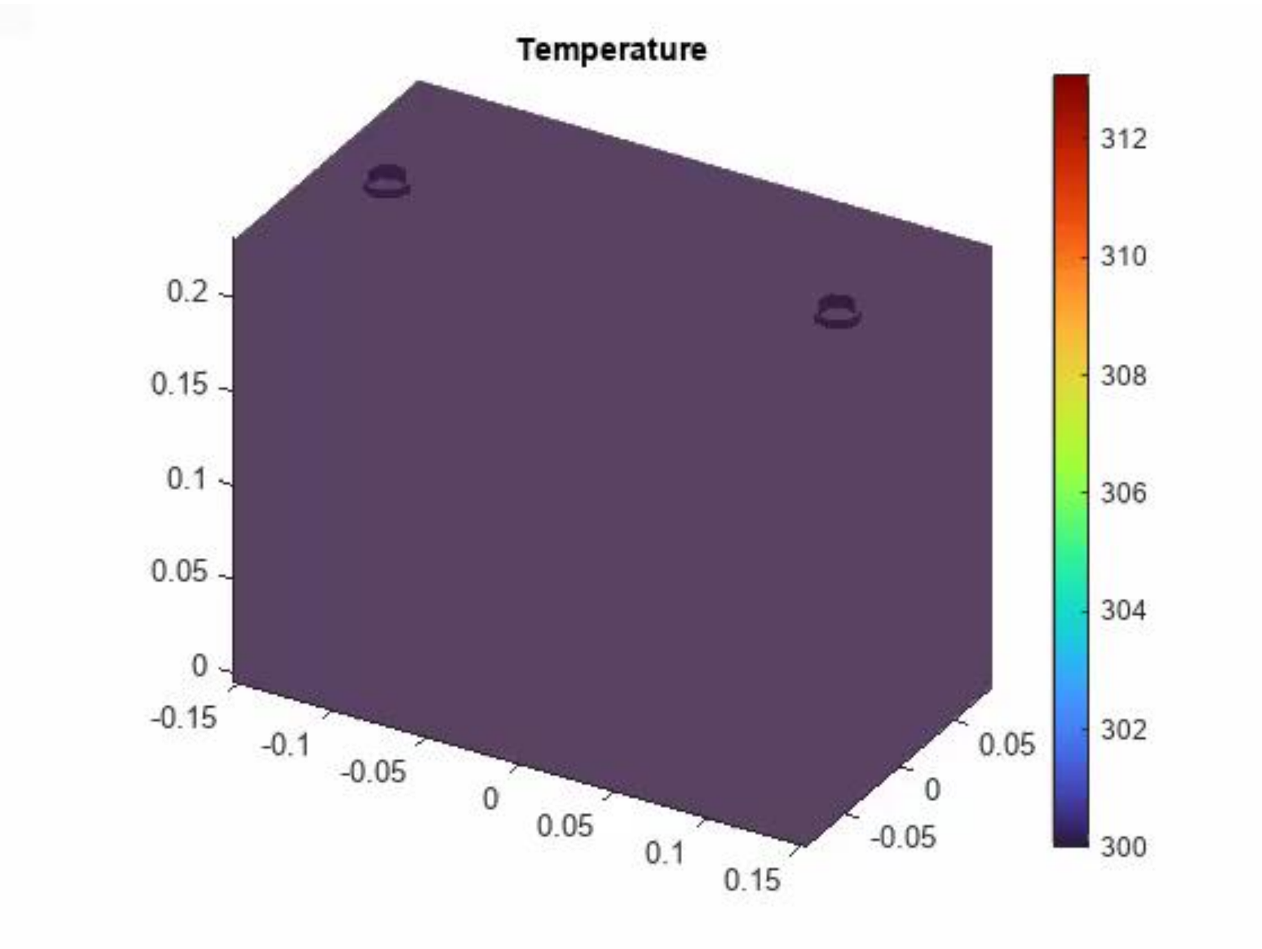
results

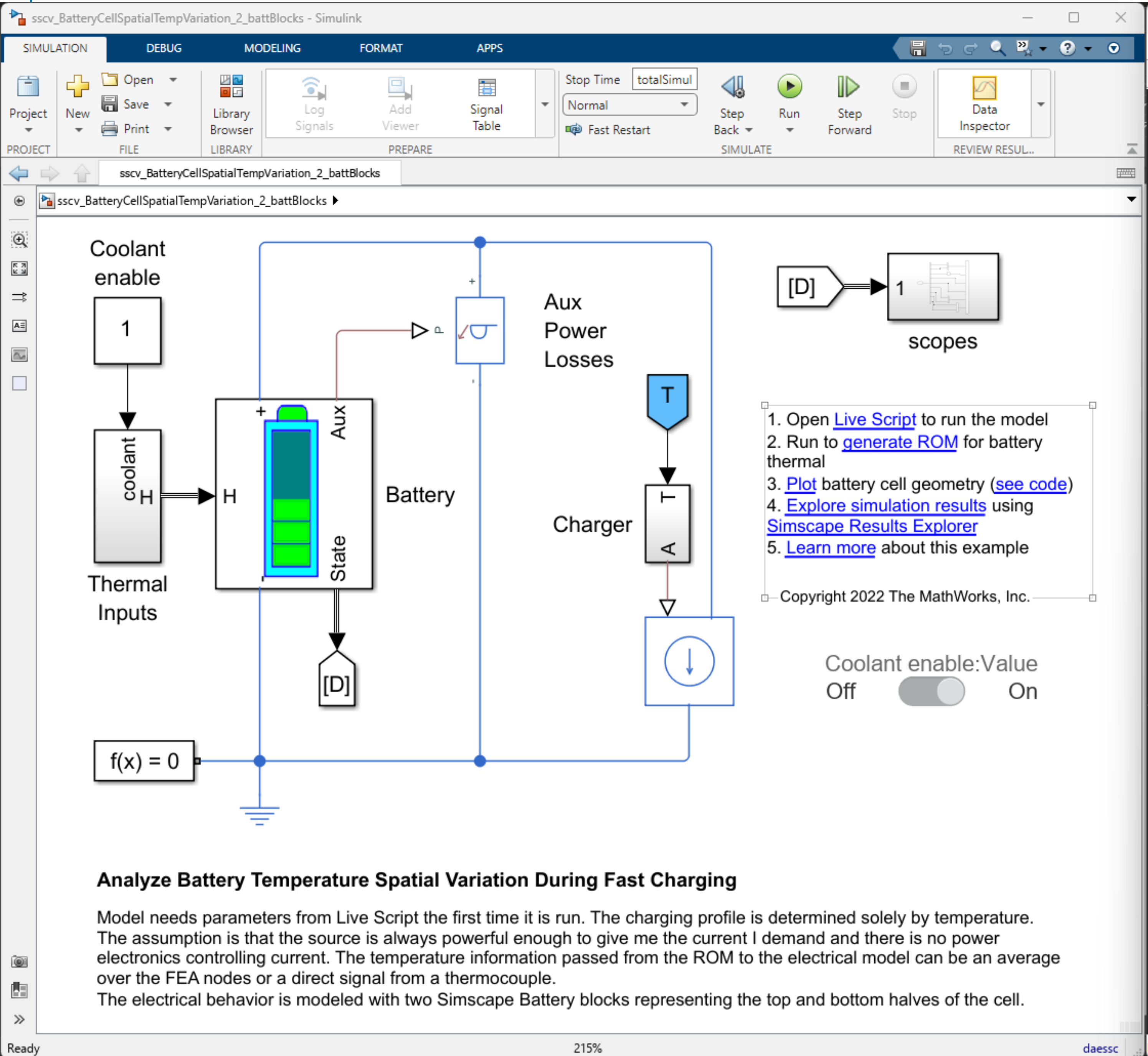
Temperature Distribution










sscv_BatteryCellSpatialTempVariation_2_battBlocks - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
APPS
Project
New
Open
Save
Print
Library Browser
Log Signals
Add Viewer
Signal Table
Stop Time
totalSimul
Normal
Fast Restart
Step Back
Run
Step Forward
Stop
Data Inspector
PROJECT
FILE
LIBRARY
PREPARE
SIMULATE
REVIEW RESUL...
Coolant enable
1
coolant
H
Thermal Inputs
Battery
Aux
State
Aux Power Losses
[D]
scopes
T
Charger
f(x) = 0
1. Open Live Script to run the model
2. Run to generate ROM for battery thermal
3. Plot battery cell geometry (see code)
4. Explore simulation results using Simscape Results Explorer
5. Learn more about this example
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Coolant enable:Value
Off
On
Analyze Battery Temperature Spatial Variation During Fast Charging
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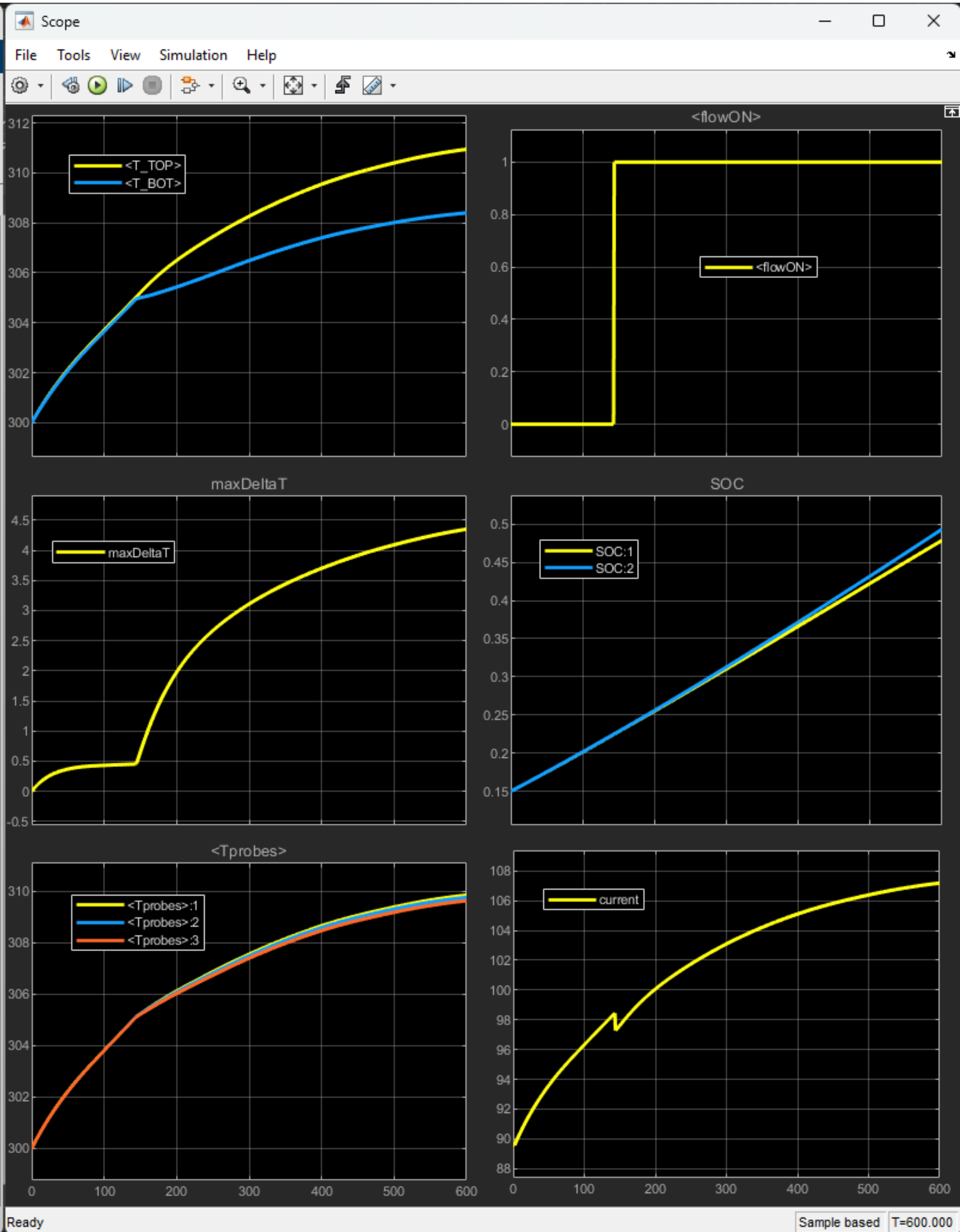
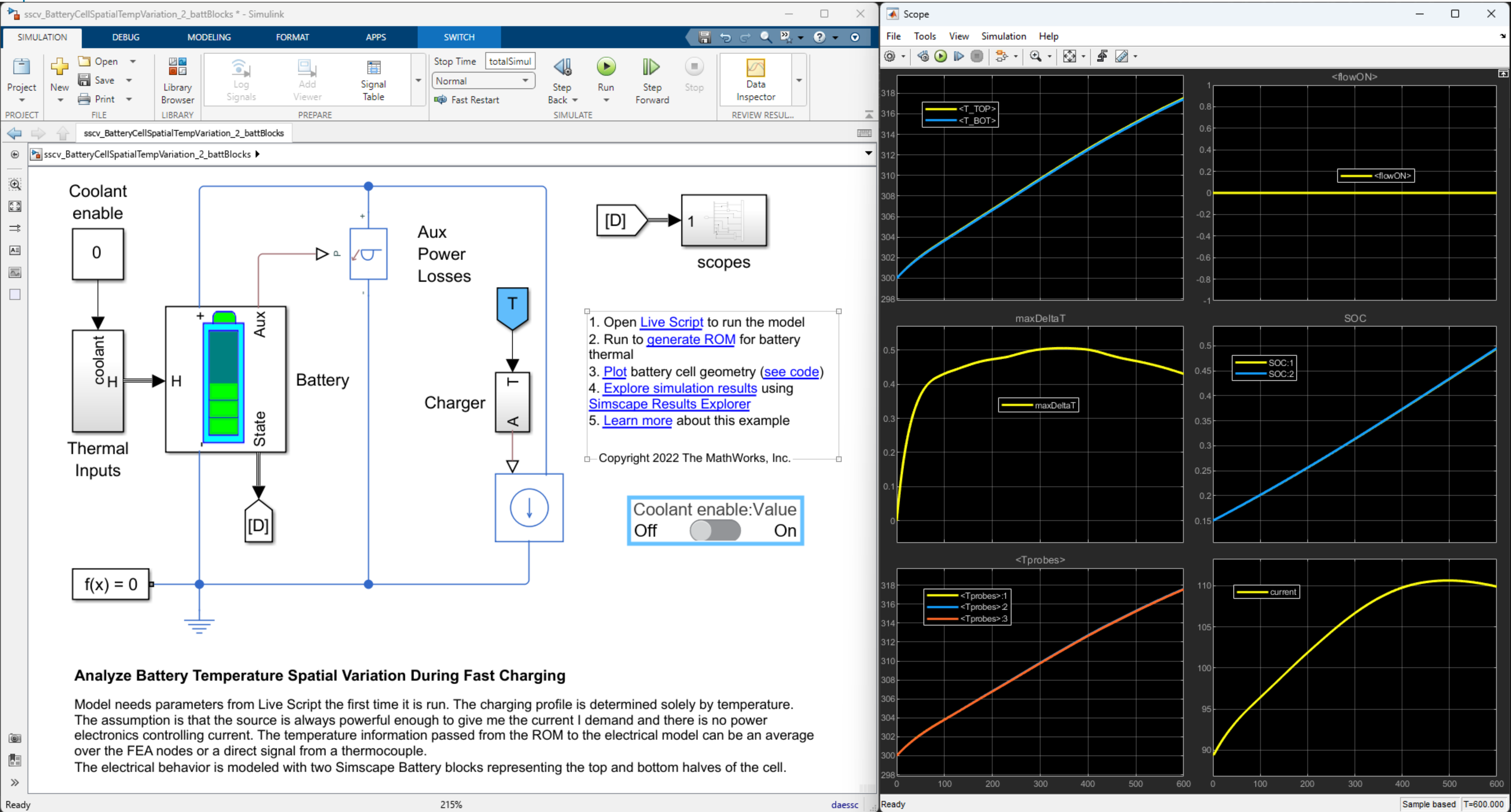
Ready
215%
daessc


Scope
File
Tools
View
Simulation
Help
<T_TOP>
<T_BOT>
<flowON>
maxDeltaT
SOC
SOC:1
SOC:2
<Tprobes>
<Tprobes>:1
<Tprobes>:2
<Tprobes>:3
current
Ready
Sample based
T=600.000


sscv_BatteryCellSpatialTempVariation_2_battBlocks * - Simulink
SIMULATION
DEBUG
MODELING
FORMAT
APPS
SWITCH
Stop Time
Normal
Fast Restart
Step Back
Run
Step Forward
Stop
Data Inspector
Coolant enable
0
coolant
H
Thermal Inputs
Battery
Aux
State
Aux Power Losses
[D]
scopes
Charger
T
A
1. Open Live Script to run the model
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Copyright 2022 The MathWorks, Inc.
Coolant enable:Value
Off
On
f(x) = 0
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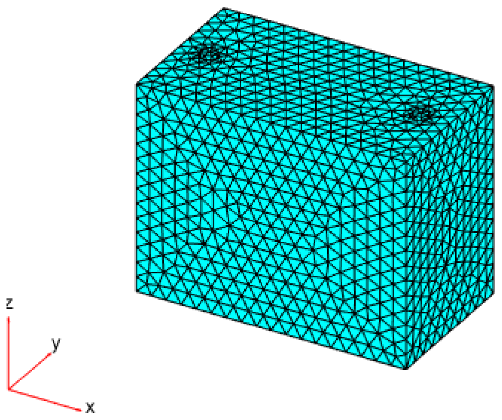
Ready
215%
daessc
Scope
File
Tools
View
Simulation
Help
<T_TOP>
<T_BOT>
<flowON>
maxDeltaT
SOC
SOC:1
SOC:2
<Tprobes>
<Tprobes>:1
<Tprobes>:2
<Tprobes>:3
current
Sample based
T=600.000

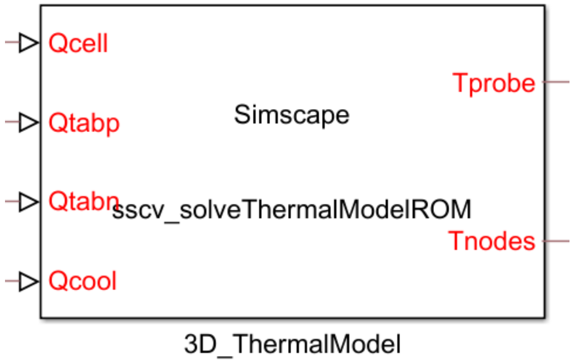
Summary

- Reduced Order Model of Battery Thermal Behavior
- FEA to System Level

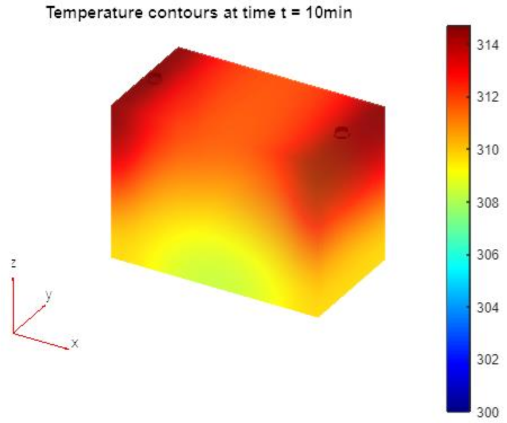



```
Rm = solve(model,'DecayRange',[-inf,0.05]);

rom = reduce(model,'ModalResults',Rm);
```



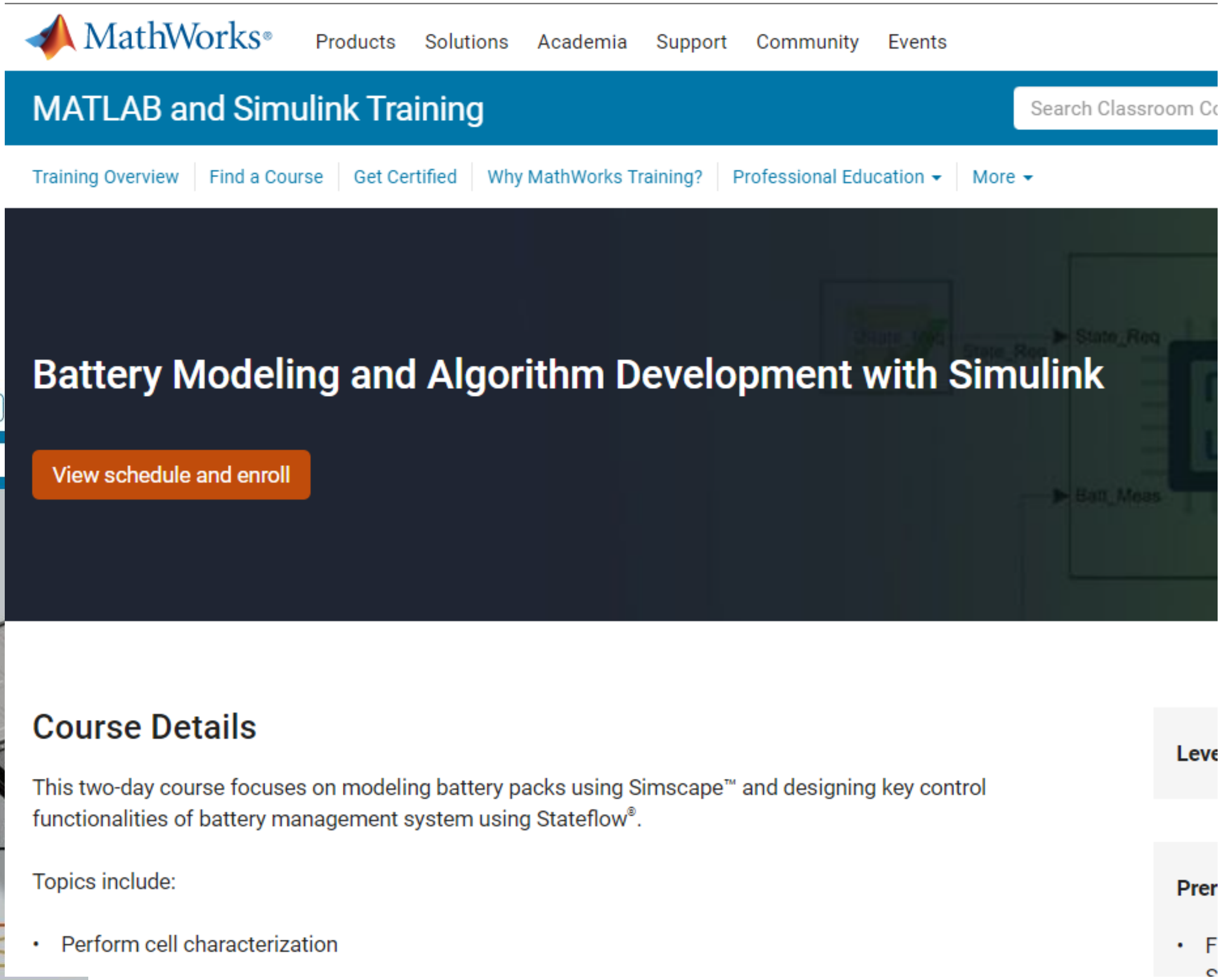
- Find Temperature Distribution
- Solve in Simulink



Outlook

- Experimental validation
- Improve geometrical description
- Electrochemical modeling
- Anything else?

Learn More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More
Battery Modeling and Algorithm Development with Simulink
View schedule and enroll
Course Details
This two-day course focuses on modeling battery packs using Simscape™ and designing key control functionalities of battery management system using Stateflow®.
Topics include:
• Perform cell characterization
Leve
Prer


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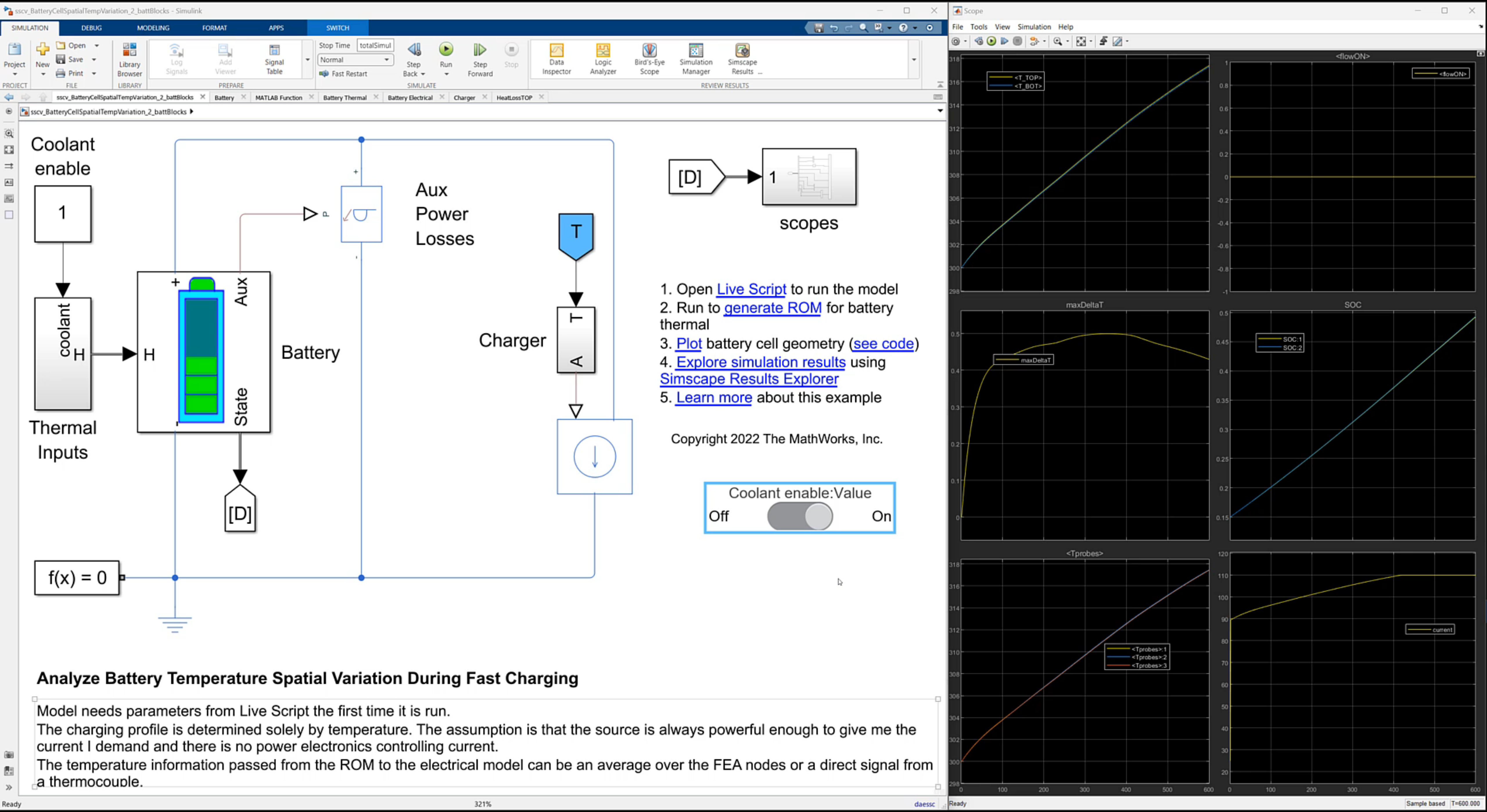
Events
Get MATLAB
Simscape Battery
Search MathWorks.com
Simscape Battery
Design and simulate battery and energy storage systems
Get a free trial
View pricing
Battery Pack
SoC
Tp
Vp
V
I
H
Simscape Battery™ provides design tools and parameterized models for designing battery systems. You can create digital twins, run virtual tests of battery pack architectures, design battery management systems, and evaluate battery system behavior across normal and fault conditions.
Battery Pack Model Builder is a design tool that lets you interactively evaluate different battery pack architectures. The tool automates the
Electrical
Battery
Fluids
Multibody
Driveline

Thank You!

Questions or Comments?

`jgazzarr@mathworks.com`

Extra Slides


sscv_BatteryCellSpatialTempVariation_2_battBlocks - Simulink
Coolant enable
1
coolant
H
Thermal Inputs
Battery
Aux
State
Aux Power Losses
Charger
T
[D]
f(x) = 0
scopes
1. Open Live Script to run the model
2. Run to generate ROM for battery thermal
3. Plot battery cell geometry (see code)
4. Explore simulation results using Simscape Results Explorer
5. Learn more about this example
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Coolant enable:Value
Off
On
Analyze Battery Temperature Spatial Variation During Fast Charging
Model needs parameters from Live Script the first time it is run.
The charging profile is determined solely by temperature. The assumption is that the source is always powerful enough to give me the current I demand and there is no power electronics controlling current.
The temperature information passed from the ROM to the electrical model can be an average over the FEA nodes or a direct signal from a thermocouple.
Scope
<flowON>
maxDeltaT
SOC
<Tprobes>