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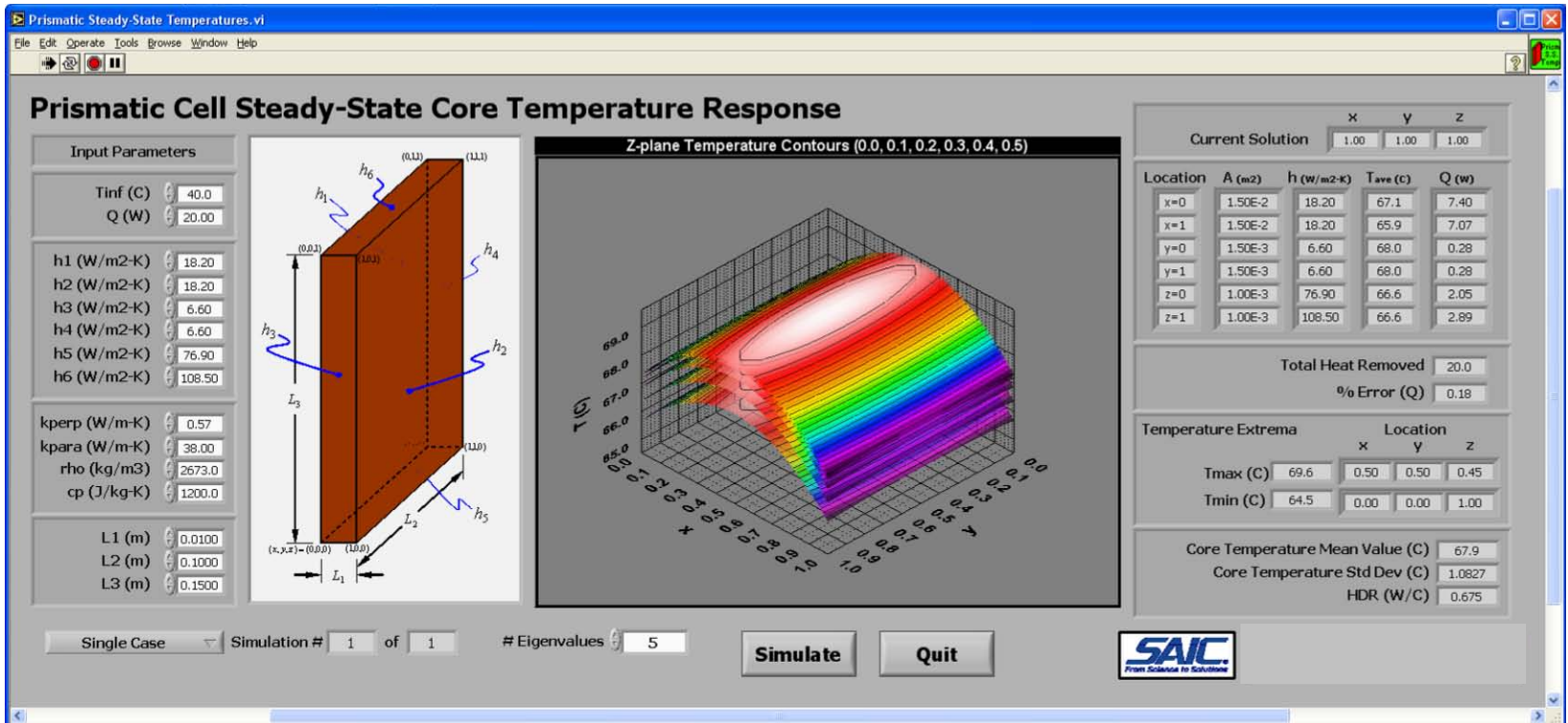
A USER-FRIENDLY TOOL FOR EVALUATING THE THERMAL RESPONSE OF HIGH POWER BATTERY PACKAGING ALTERNATIVES

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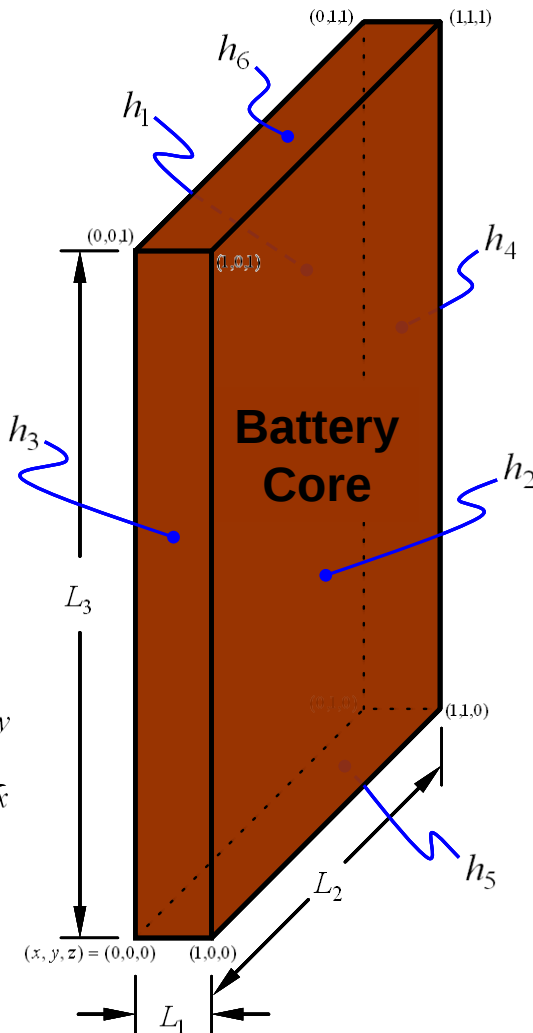
- Latest generation of high power battery cells are often comprised of multiple alternating layers of anode, cathode, separator and electrolyte
- Macroscopically, battery cores represent an orthotropic material subject to a time variant heat source
- Safety and performance considerations place a premium on packaging design and installation thermal maintenance
- SAIC has developed a numerical solver tool to evaluate thermal performance of packaging alternatives that will:
 - Run rapidly (avoiding costly finite element simulations)
 - Evaluate multiple geometries (prismatic, cylindrical, annular cell arrangements)
 - Provide flexibility for multiple configurations (air or liquid cooling)
 - Support steady-state and transient solutions
 - Quantify predictive uncertainty
- Allows for internal cell temperature prediction where instrumentation is difficult, at best

Cartesian Steady-State Solver for Prismatic Battery Cells



- Solver predicts temperature response within the battery core based upon user supplied input of geometry, cell properties, boundary conditions and heating rate
- User can select mesh refinement and degree of simulation precision

Cartesian Solver for Prismatic Battery Cells



- Solves for temperature profiles as a function of coolant temperature, heating rate, effective boundary conditions and cell properties

$$\rho c_p \frac{\partial T}{\partial t} = k_{\perp} \frac{\partial^2 T}{\partial x^2} + k_{\parallel} \frac{\partial^2 T}{\partial y^2} + k_{\parallel} \frac{\partial^2 T}{\partial z^2} + \dot{Q}_v(t)$$

- The solution solves for temperature response with effective convective boundary conditions along all six faces of the cell core utilizing boundary conditions of the third kind

$$k_{\perp} \frac{\partial T}{\partial x} \Big|_{x=0} = h_1(T_1 - T_{\infty}) \quad , \quad -k_{\perp} \frac{\partial T}{\partial x} \Big|_{x=L_1} = h_2(T_2 - T_{\infty})$$

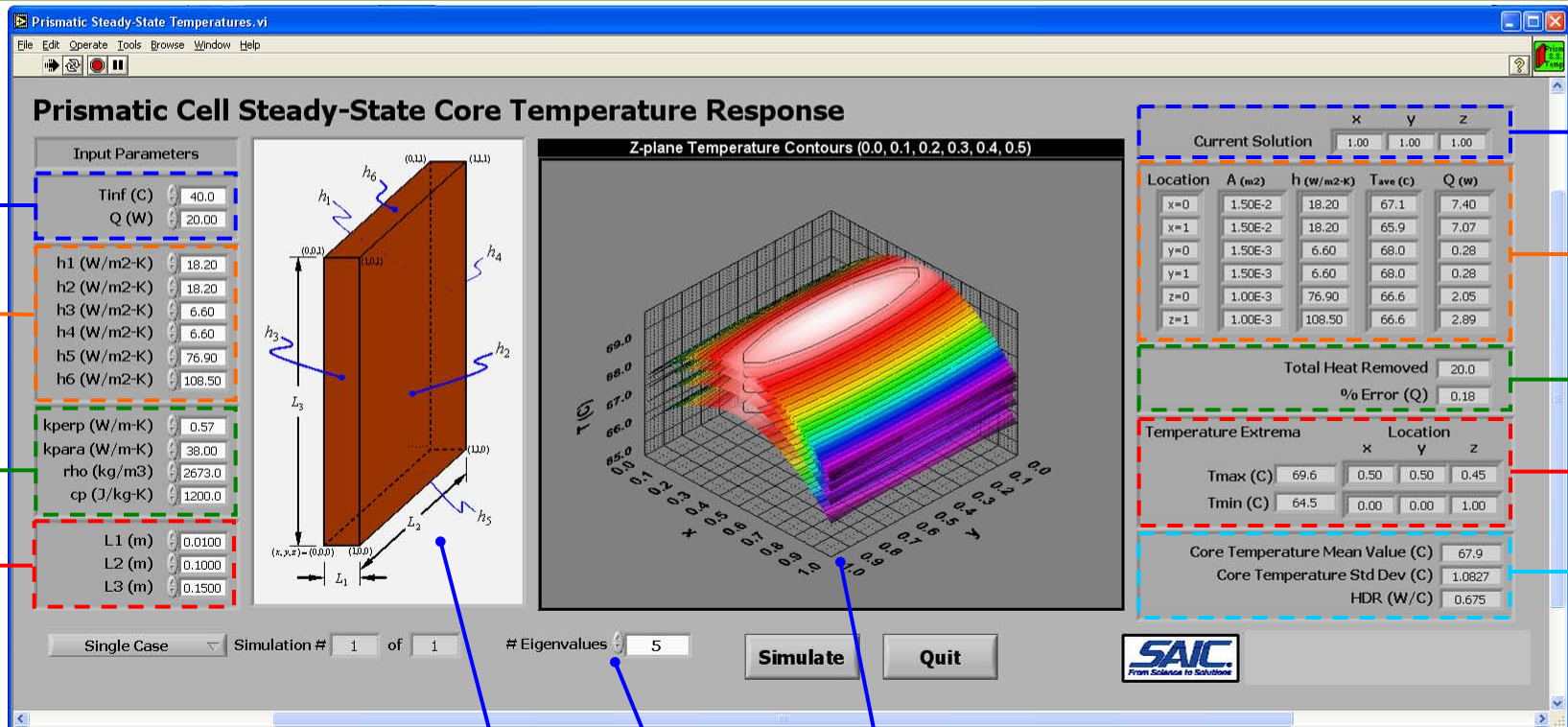
$$k_{\parallel} \frac{\partial T}{\partial y} \Big|_{y=0} = h_3(T_3 - T_{\infty}) \quad , \quad -k_{\parallel} \frac{\partial T}{\partial y} \Big|_{y=L_2} = h_4(T_4 - T_{\infty})$$

$$k_{\parallel} \frac{\partial T}{\partial z} \Big|_{z=0} = h_5(T_5 - T_{\infty}) \quad , \quad -k_{\parallel} \frac{\partial T}{\partial z} \Big|_{z=L_3} = h_6(T_6 - T_{\infty})$$

- Similar forms exist for cylindrical cells

Cartesian Steady-State Solver for Prismatic Battery Cells

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Battery Dimensions

Battery Core Properties

Effective Heat Transfer Coefficients

Problem Specifications

Geometry
Depiction

Number of Eigenvalues
(per coordinate direction)

Dimensionless Temperature Profiles
 $T = f(x/L_1, y/L_2)$
at $z/L_3 = (0.0, 0.1, 0.2, 0.3, 0.4, 0.5)$

Core Temperature Statistics

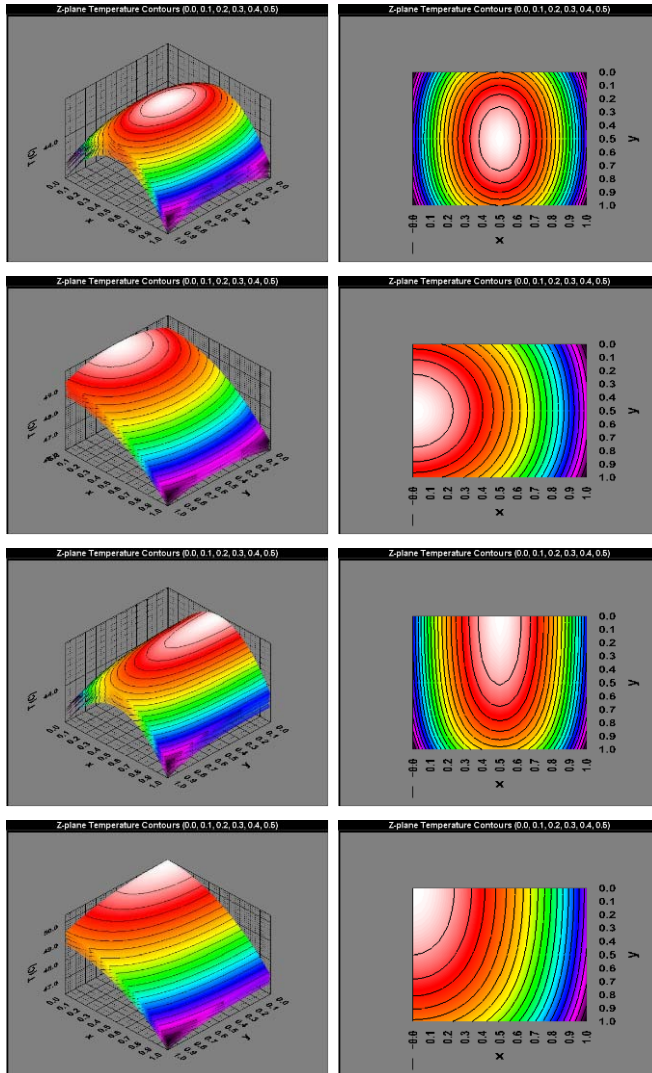
Temperature Extrema and Locations

Energy Balance Solution Check

Core Face Values

Solution Location Monitor

Results of Several Baseline Verification Simulations



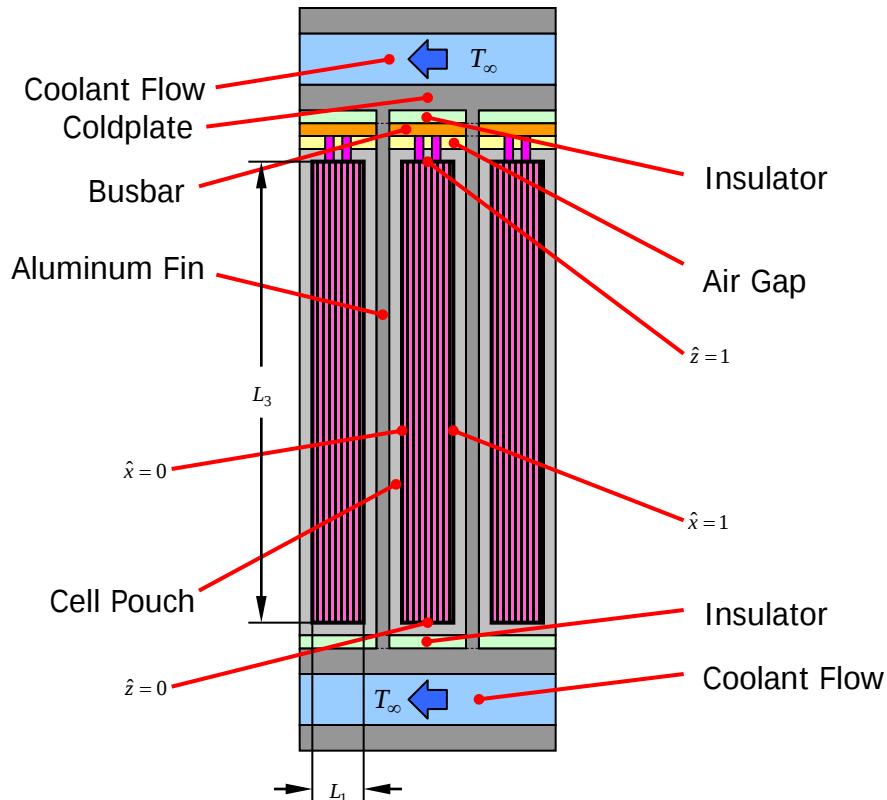
- Uniform heat transfer coefficients
 - Note increased gradients in x-direction due to orthotropic properties
- Adiabatic conditions along $x=0$ face
- Adiabatic conditions along $y=0$ face
- Adiabatic conditions along $x=0$ & $y=0$ face

Solver Example – Prismatic Cells Between Liquid Coldplates

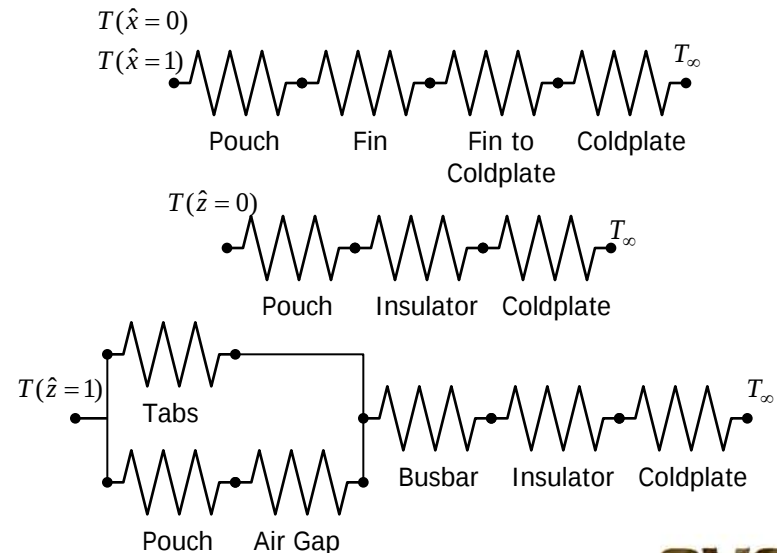
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- A generic prismatic cell (15×10×1 cm) with sandwiched between cold plates – aluminum interstitial plates act as cooling fins for cell lateral surfaces
- Effective heat transfer coefficients estimated through analogous thermal circuits
- Similar approach used for y-direction effective heat transfer coefficients



$$\frac{1}{h_{eff} A} = \sum_n \frac{1}{h_n A_n} + \sum_m \frac{\Delta x}{k_m A_m}$$



Monte Carlo Simulation Tool

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- To quantify uncertainty, a Monte Carlo simulation tool has been developed
- User selects distribution type and parameters
- Currently supports:
 - Gaussian distributions
 - Log-normal distributions
 - Uniform distributions
- User tool has distribution samples to aid user identification
- User selects number of Monte Carlo samples to simulate

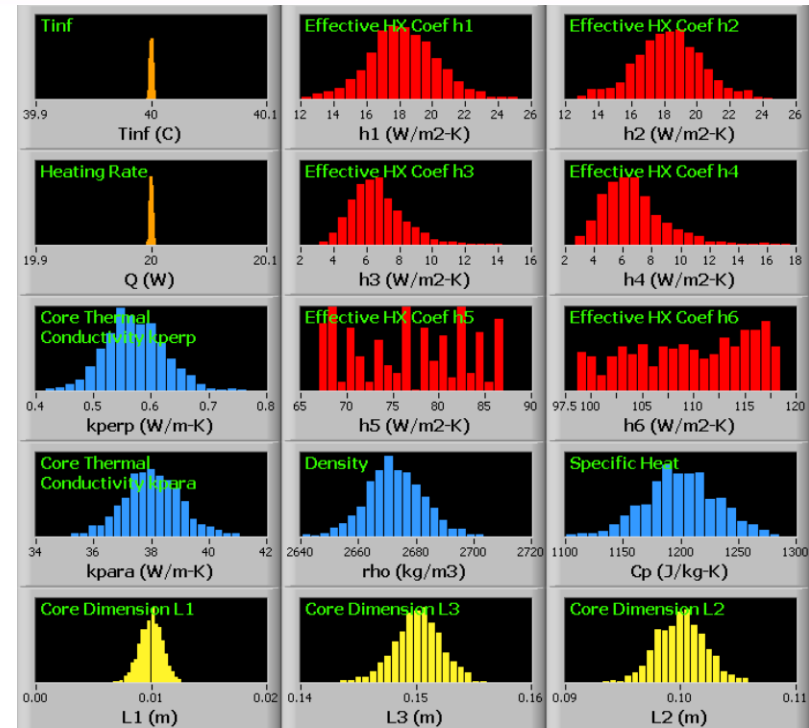
The screenshot displays the 'Prismatic Monte Carlo.vi' software interface. The main window is titled 'Distribution Parameters' and contains several sections:

- Calculate/OK Buttons:** Located on the left side of the parameter table.
- Number of Samples:** A slider control set to 1000.
- Distribution Parameters Table:** A table with columns for parameter names, Mean or Low, Std Dev or High, and Distribution Type. Parameters include Tinf (C), Q (W), h1 (W/m2-K), h2 (W/m2-K), h3 (W/m2-K), h4 (W/m2-K), h5 (W/m2-K), h6 (W/m2-K), kperp (W/m-K), kpara (W/m-K), rho (kg/m3), cp (J/kg-K), L1 (m), L2 (m), and L3 (m).
- Input Variable Array Sample:** A table showing 10 columns of numerical data representing samples for various input variables.
- Instructions:** A list of steps: (1) Specify distribution type and parameters, (2) Push Calculate, (3) Repeat (1) & (2) until satisfied, (4) Push OK.
- Summary Statistics:** Mean, Std Dev, Mean of ln(x), Std Dev of ln(x), High, and Low values for the selected distribution.
- Distribution Plots:** Three histograms showing the distribution of samples for Normal, Log-Normal, and Uniform distributions.

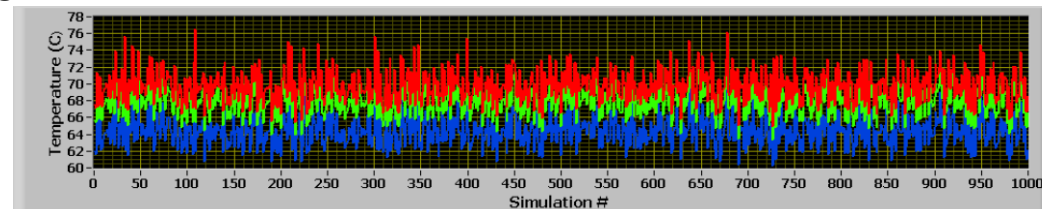
Monte Carlo Simulation
Distribution Parameters Input Screen

Monte Carlo Simulation Results

- Monte Carlo simulation runs multiple simulations using random sampling from defined variable distributions
- Simulations run rapidly – 1000 samples runs in a matter of minutes on a laptop
- Allows for rapid evaluation of uncertainty
 - Material properties
 - Heating rate
 - Boundary conditions
- Solver plots battery cell maximum, minimum and average temperature



Input Property Distributions

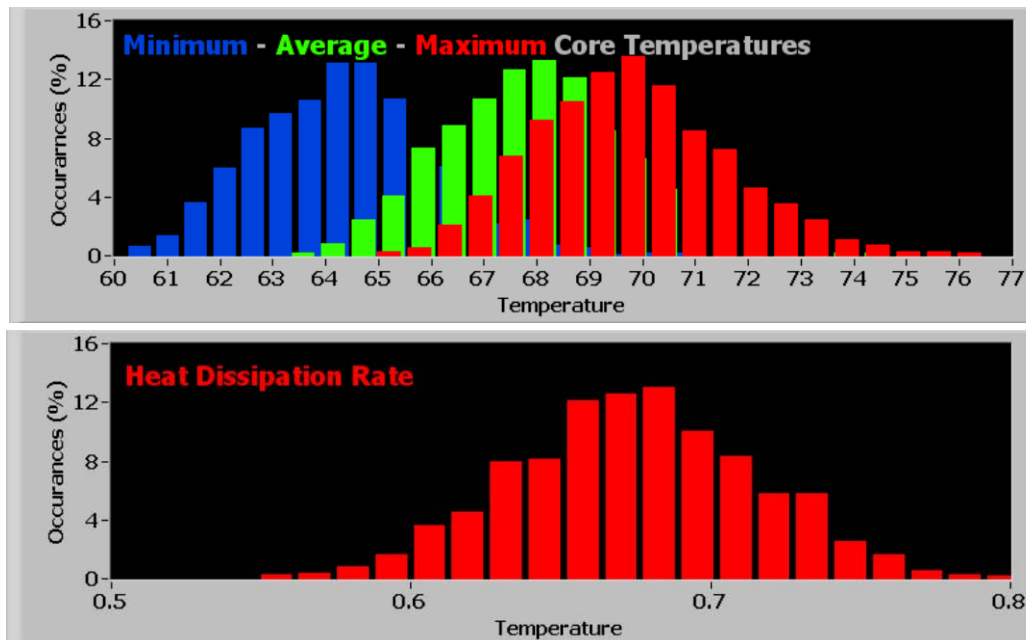


Monte Carlo Simulation Results

Monte Carlo Simulation Results



- The solver post-processes the Monte Carlo simulation results to give:
 - Distributions for the minimum, average and maximum core temperatures
 - Heat Dissipation Rate (HDR) distribution
 - Parameters of those distributions (mean and standard deviation)



Tmax mean	69.77
Tmax std dev	1.83
Tave mean	68.03
Tave std dev	1.80
Tmin mean	64.39
Tmin std dev	1.72
HDR mean	0.67
HDR std dev	0.04

**Distribution
Parameters**

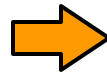
- Heat Dissipation Rate (HDR) is a measure of the package cooling effectiveness and is defined as:

$$HDR = \frac{\dot{Q}}{T_{Max} - T_{Coolant}}$$

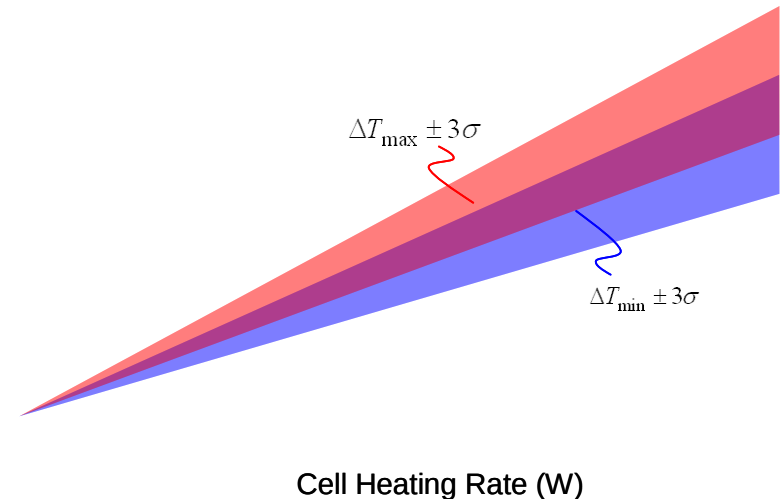
Utilizing Results

- Heat Dissipation Rate (HDR) can be used to quantify the expected temperature difference from the cell to the coolant as a function of heating rate
- HDR leads to predictive of maximum and minimum core temperatures as a function of heating rate with uncertainty bounds ($\pm 3\sigma$)

$$HDR = \frac{\dot{Q}}{T_{Max} - T_{Coolant}}$$



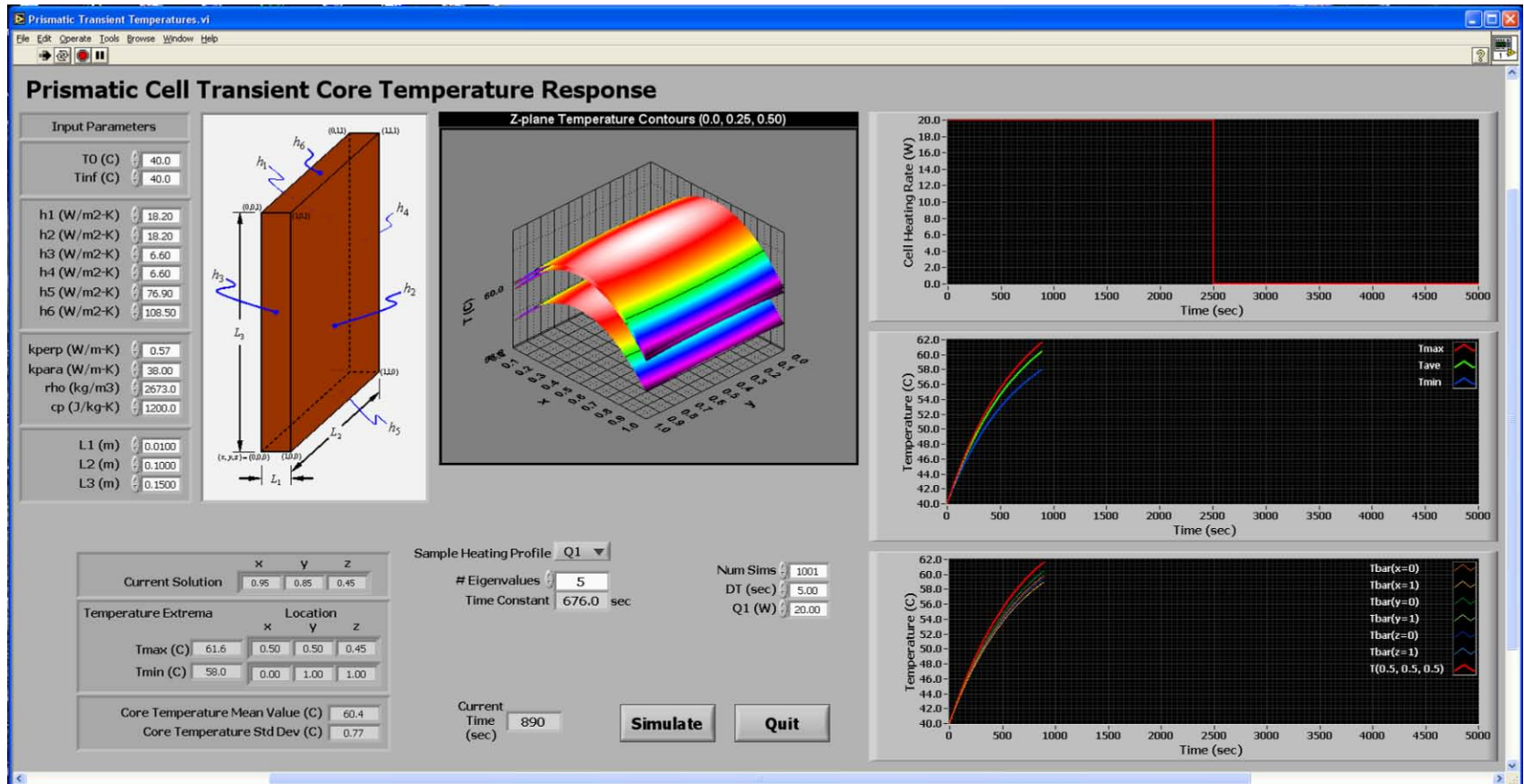
Temperature
Difference
to Coolant
(°C)



- This illustrates best- and worst-case cooling scenarios for this particular packaging design
- For example, at a 30°C coolant temperature and a 15W cell heat load
 - ΔT_{max} (Cell max temperature – Coolant Temperature) = 27 °C
 - Worst-case maximum core temperature is predicted to be $48 < T_{max} < 57^{\circ}\text{C}$.

Cartesian Transient Solver for Prismatic Battery Cells

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- Allows for transient simulation of time-variant heat loads
- Heat loads can be user defined or uploaded from tab-delimited files

GVSETS

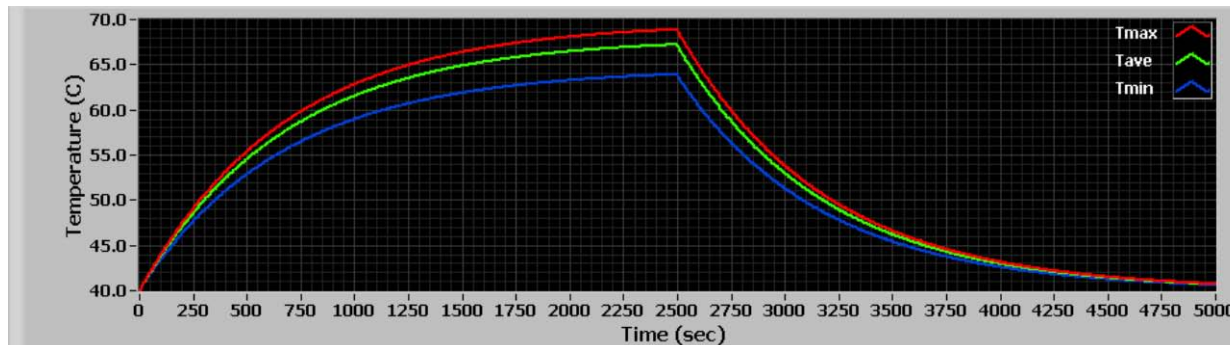
Transient Results Step Discharge Case



- Results of a step change in heating from initial conditions



Cell Heating Rate



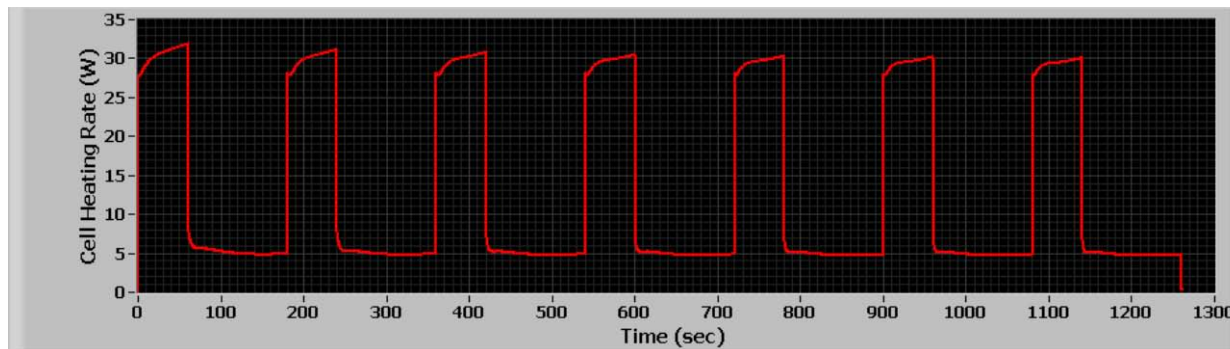
Battery Core Temperature Response

- Identifies battery packaging concept time constant, worst case loading expectations and recovery time

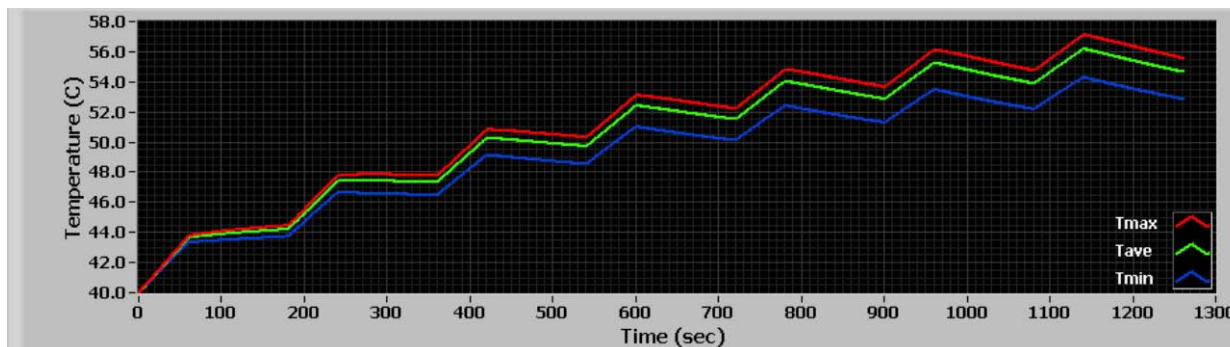
Transient Results Load Leveling Case



- Load-leveling presents a challenging thermal demand
- This case represents the temperature response to repetitive cycles of 60 sec discharge (100A) and 120 sec charge (50A)



Cell Heating Rate

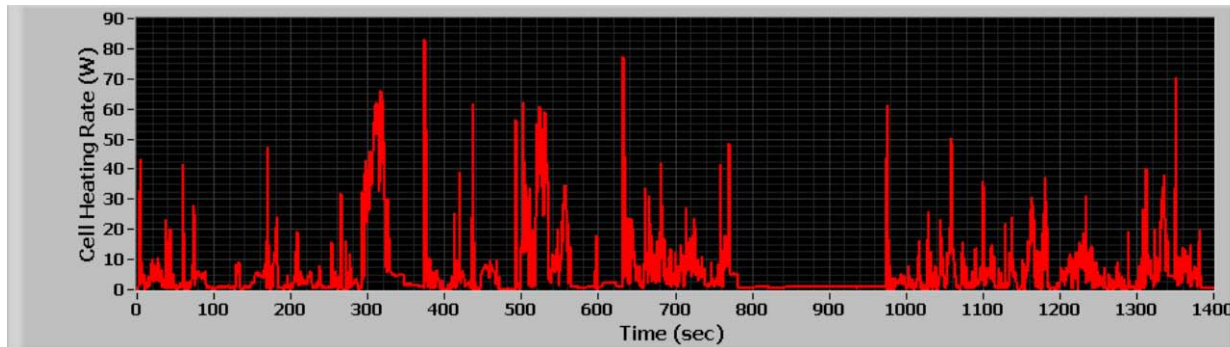


Battery Core Temperature Response

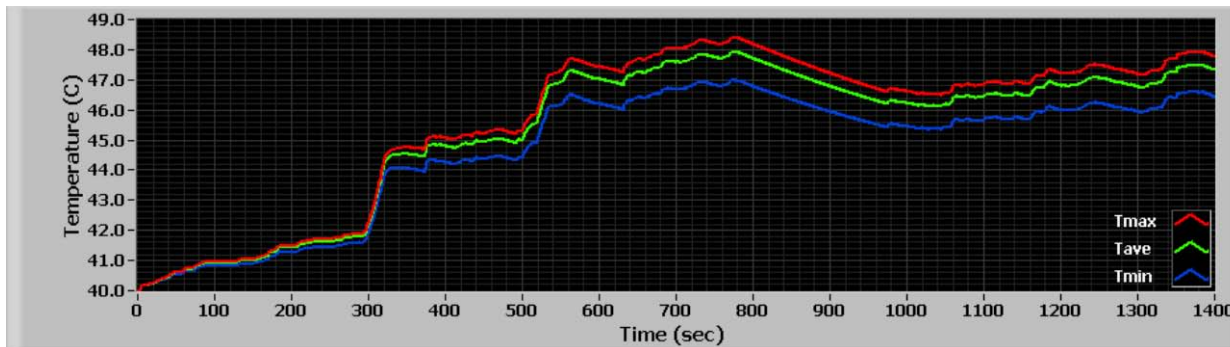
Transient Results Driving Scenario Case



- Realistic driving scenarios imposed on a battery used for mobility assist
- Profiles typically show extensive non-uniformity



Cell Heating Rate



Battery Core Temperature Response



- Thermal solver predicts internal battery core temperature response
- Steady-state and transient applications
- Different geometries supported – prismatic, cylindrical, annular
- Monte Carlo simulator included to quantify uncertainty
- Several future developments are envisioned:
 - Link to battery performance tool (electrical model)
 - User tools to support boundary condition estimation
 - Inclusion of transient coolant temperatures
 - Temperature dependent property effects
 - External package thermal inertia effects
- Questions / Comments / Feedback