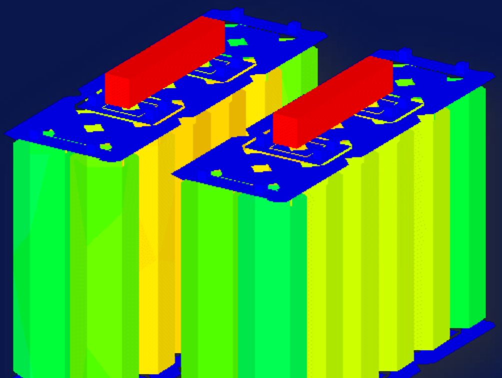
ThermoAnalytics® Total Thermal Solutions

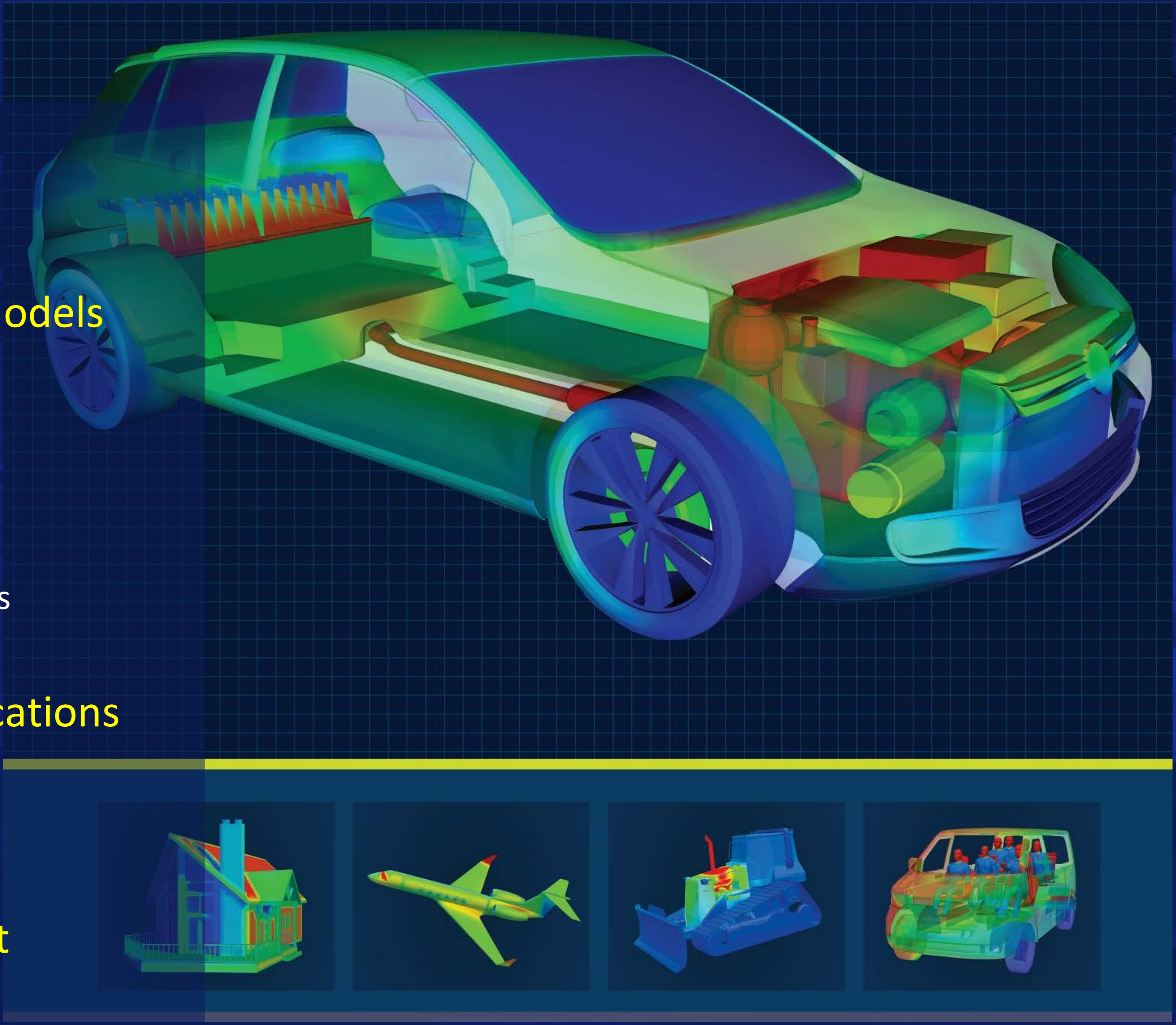
All Things Battery with TAITherm

Scott Peck



Agenda

- Background
  - Design issues
  - Modeling issues
- TAITherm Battery Models
  - Physical description
  - Modeling concepts
  - Relative strengths
- Input Requirements
  - Electrical parameters
  - Thermal parameters
- Use in Typical Applications
  - Single cells
  - Pack / module
  - System integration
- Future Development
  - Runaway model
  - Life model



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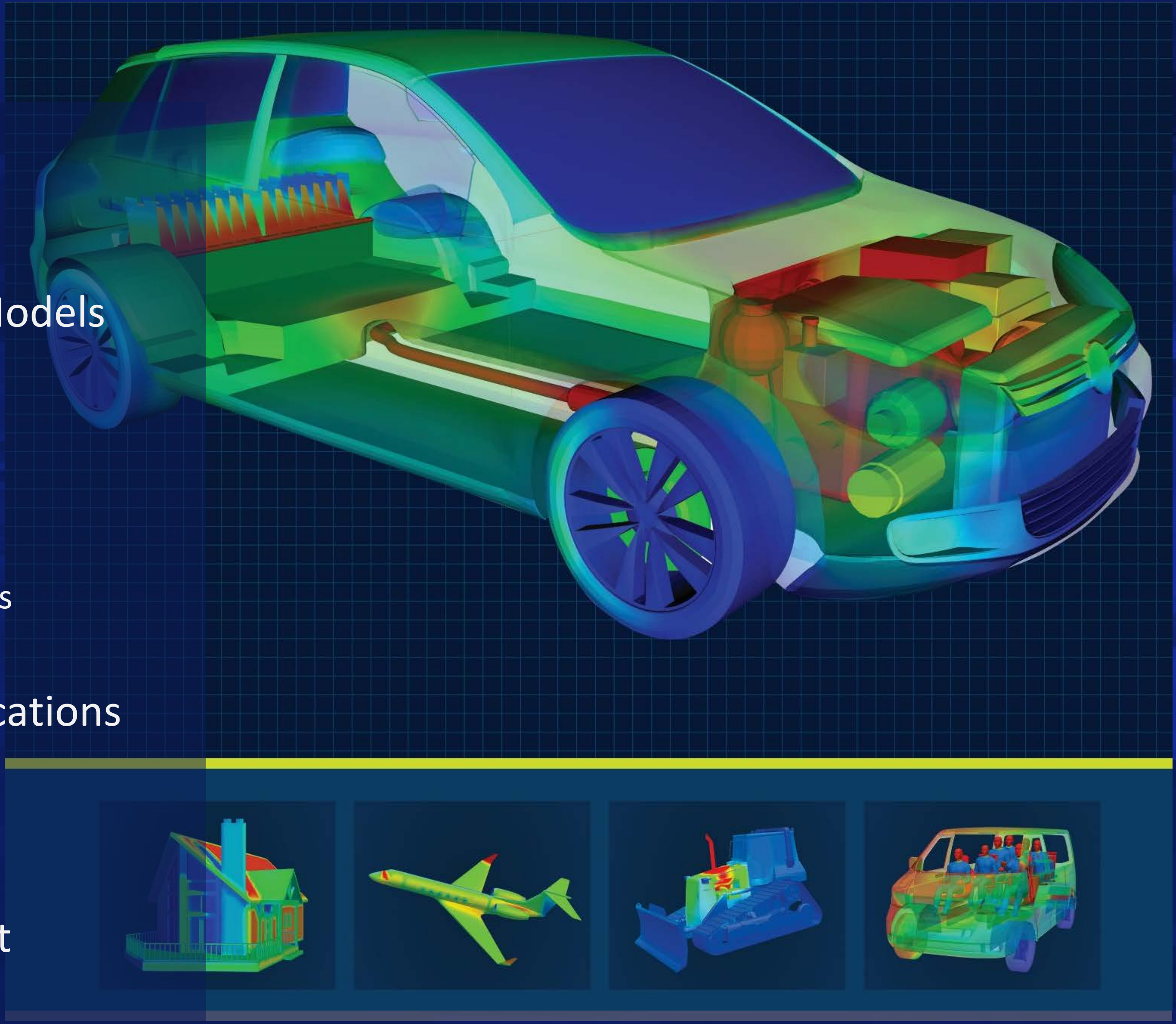

Purpose of Battery Modeling
Electric Vehicle Problems – All Thermal Problems

2014

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Should Battery Fires Drive Electric Cars Off the Road?

Of the more than 150,000 car fires in the U.S. this year, one got all the attention

November 12, 2013 | By David Biello

The Seattle Times
Winner of Nine Pulitzer Prizes

Business / Tech

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Originally published May 22, 2014 at 11:18 AM | Page modified May 23, 2014 at 11:04 AM

NTSB: Stiffer tests may be needed for lithium-ion plane batteries

A new NTSB report says the government relied too much on Boeing for technical expertise when it certified the 787's lithium-ion batteries as safe. The report also said the standard for certifying and testing such batteries on airplanes may not be adequate.

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March 10, 2013

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Can electric vehicles withstand the Indian heat?

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TOPICS

economy, business and finance

manufacturing and engineering

With the unveiling of the National Electric Mobility Mission Plan 2020, Prime Minister Manmohan Singh has urged manufacturers to adopt electric vehicles in an attempt to reduce our dependence on imported oil. The ambitious plan aims to produce 6-7 million electric vehicles by 2020 with an estimated fuel savings of 2.2-2.5 million tonnes. Vehicle manufacturers in India have a tough road ahead in meeting this goal and tailoring electric vehicles for the Indian market.

REUTERS

EDITION: U.S.

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Tesla grapples with impact of battery fire in U.S.

BY BEN KLAYMAN

DETROIT | Thu Oct 3, 2013 4:58pm EDT

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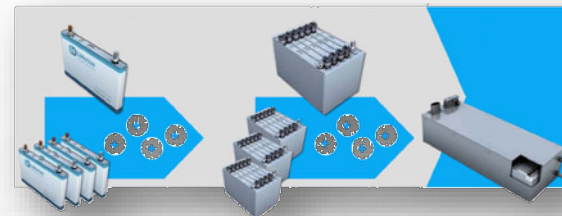
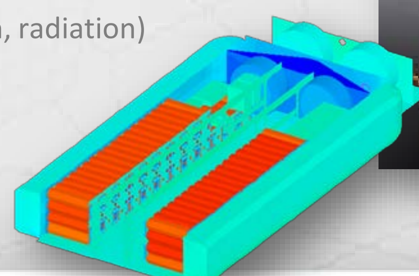
Battery Design Issues Occur at Different Time and Length Scales

- **Electrode-level issues**
  - Coupled electro-chemical diffusion processes
    - Ion transport, charge depletion, etc.
  - Materials
  - Length scale ~ electrode pore size
- **Cell-level issues**
  - Local potential differences between electrodes
  - Distribution of current density (and heating)
  - Distribution of capacity / state-of-charge
  - Local temperature
  - Abuse tolerance (overcharge or overdischarge, crush)
  - Length scale ~ cell dimensions
- **Pack-level issues**
  - Cell-to-cell variations
    - Terminal voltage
    - Thermal boundary conditions (convection, conduction, radiation)
    - Cell history
  - Drive cycle load
  - Propagation of thermal runaway
  - Length scale ~ pack dimensions





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Battery Model Applies to Different Topologies

- Pouch
  - Alternating layers of cathode and anode
  - Multiple layers in parallel
  - Contained in flexible pouch
- Prismatic
  - 'Jellyroll' flattened inside rigid can structure (racetrack)
- Cylindrical
  - Jellyroll wound around a central post
  - Contained in rigid can
  - 18650: 18mm dia, 650 mm height
- Chemistries
  - Li-ion flavors, NiMH, alkaline, lead-acid

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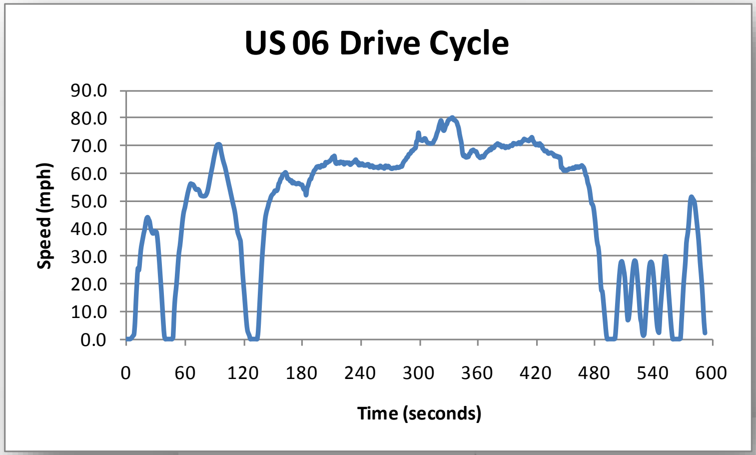
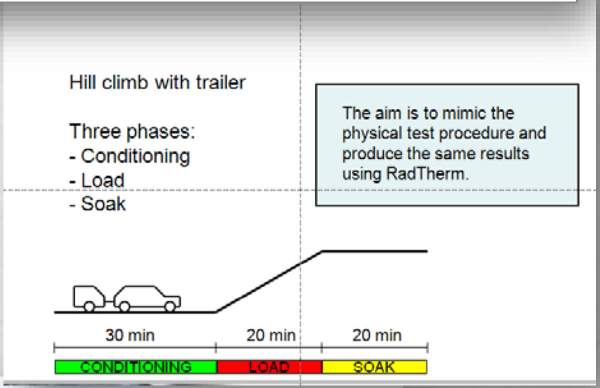
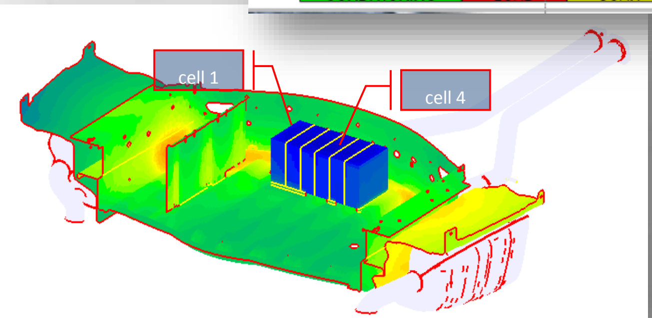
Battery Model Thermal Scenarios

- Batteries are transient devices
  - Cooling System Faults
  - Drive Cycles
  - Load Balancing
    - Avoiding overcharge/discharge
  - Hot Soak
    - Time at temperature reduces life
  - Preheating for Cold Start
    - Cold batteries lose capacity
  - Abuse Tolerance
  - Thermal Runaway







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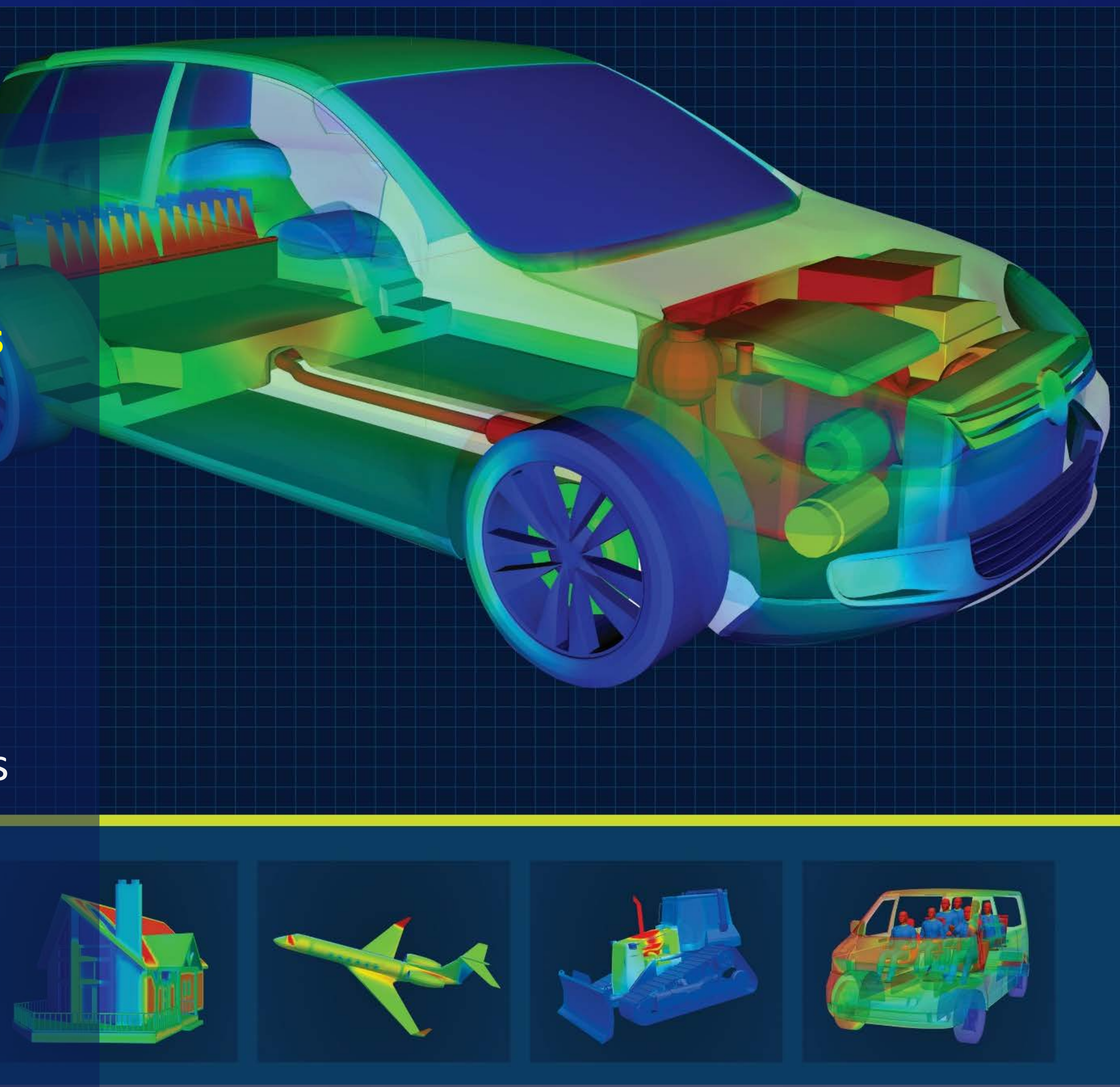
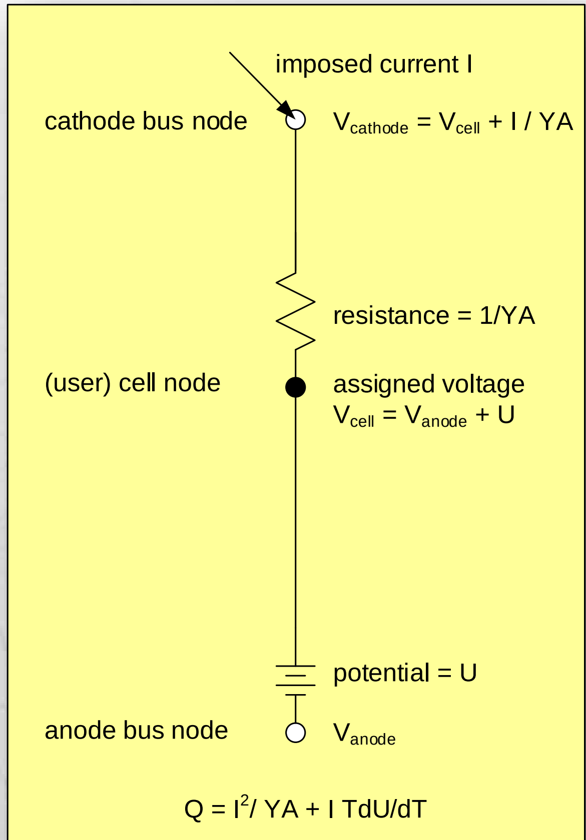


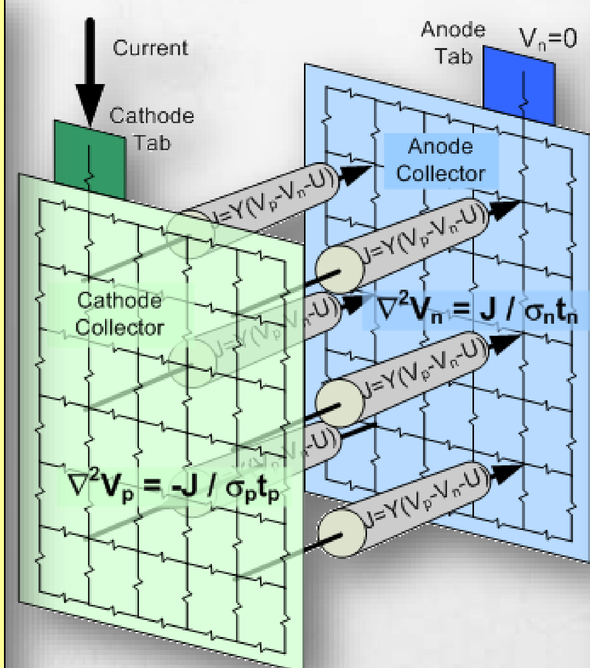
Battery Model Overview

TAITherm supports 3 battery models:

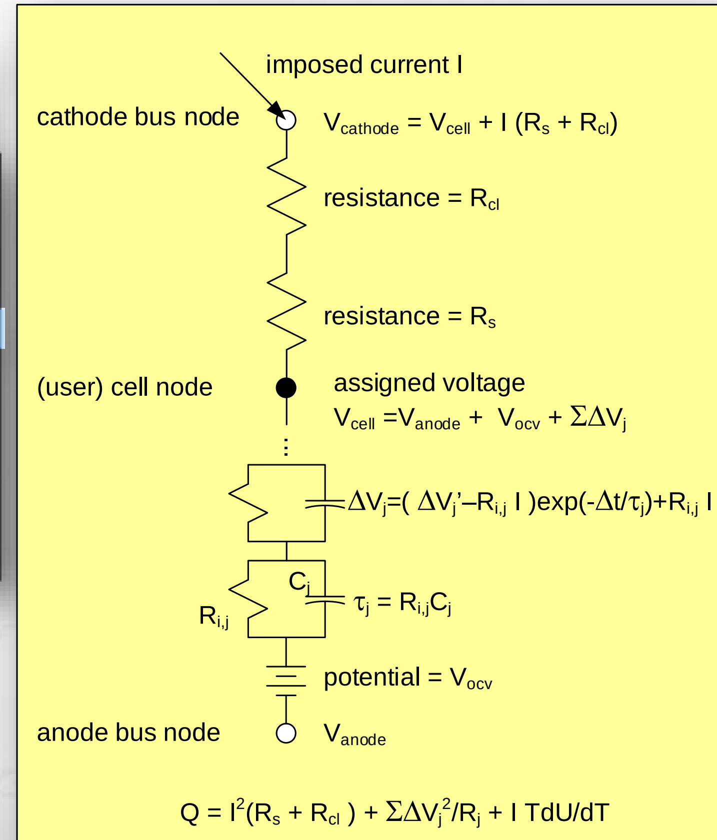
NTG Equivalent Circuit Model



NTG Distributed Model



NREL Equivalent Circuit Model

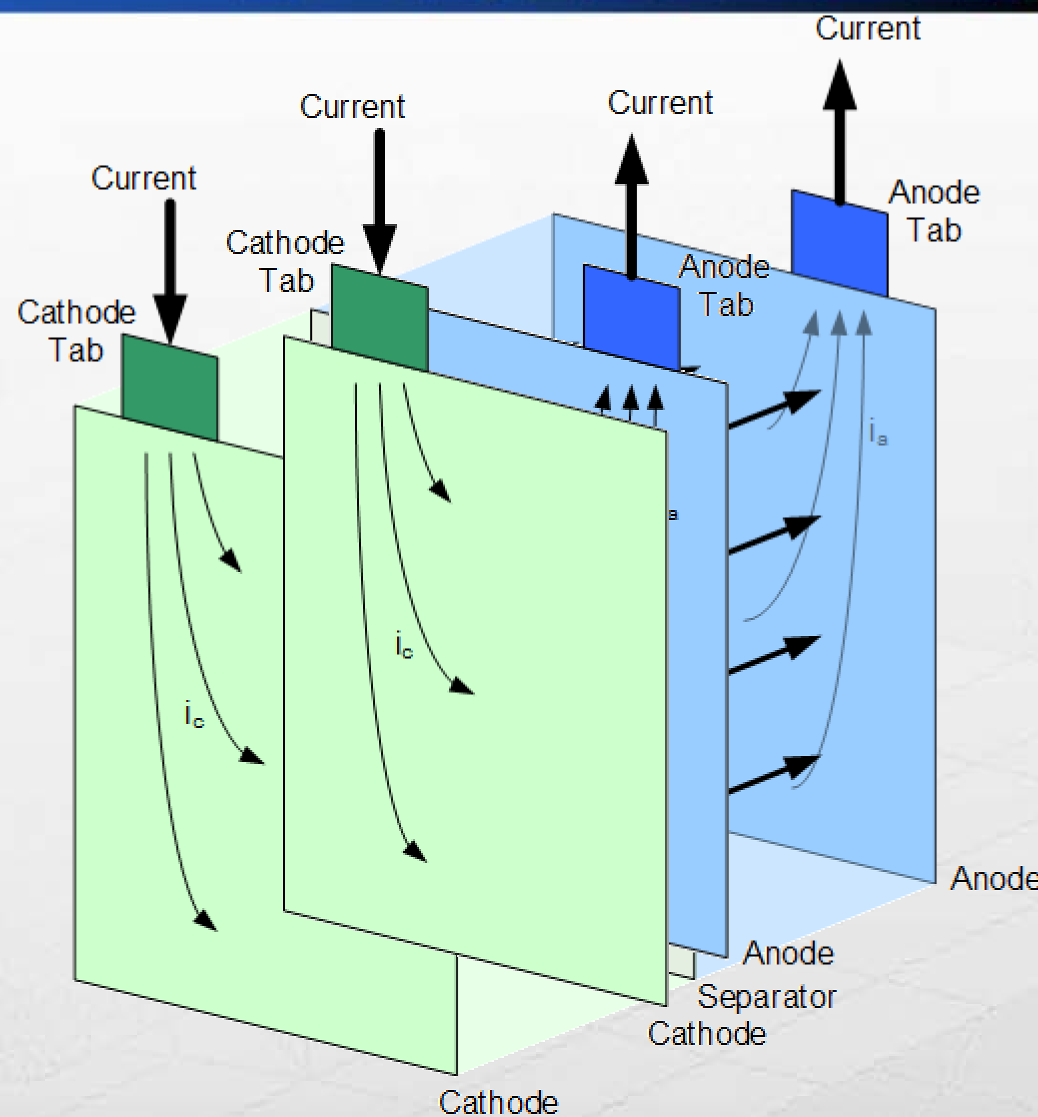


Battery Models in TAITherm

- Empirical
  - Model parameters derived from measured performance data
- Electrical and thermal behaviors are coupled
  - Battery resistance depends on temperature and depth of discharge
  - Temperature depends on heating from I^2R and chemical reactions
- Battery models compute an imposed heat on the battery geometry
  - To compute the imposed heat, some electrical circuit equations must be solved simultaneously
    - Equivalent circuit models have one circuit equation per cell, and one value of heat applied to the entire cell
    - Distributed model have as many circuit equations as there are elements describing the electrodes, and the heat is computed for each element

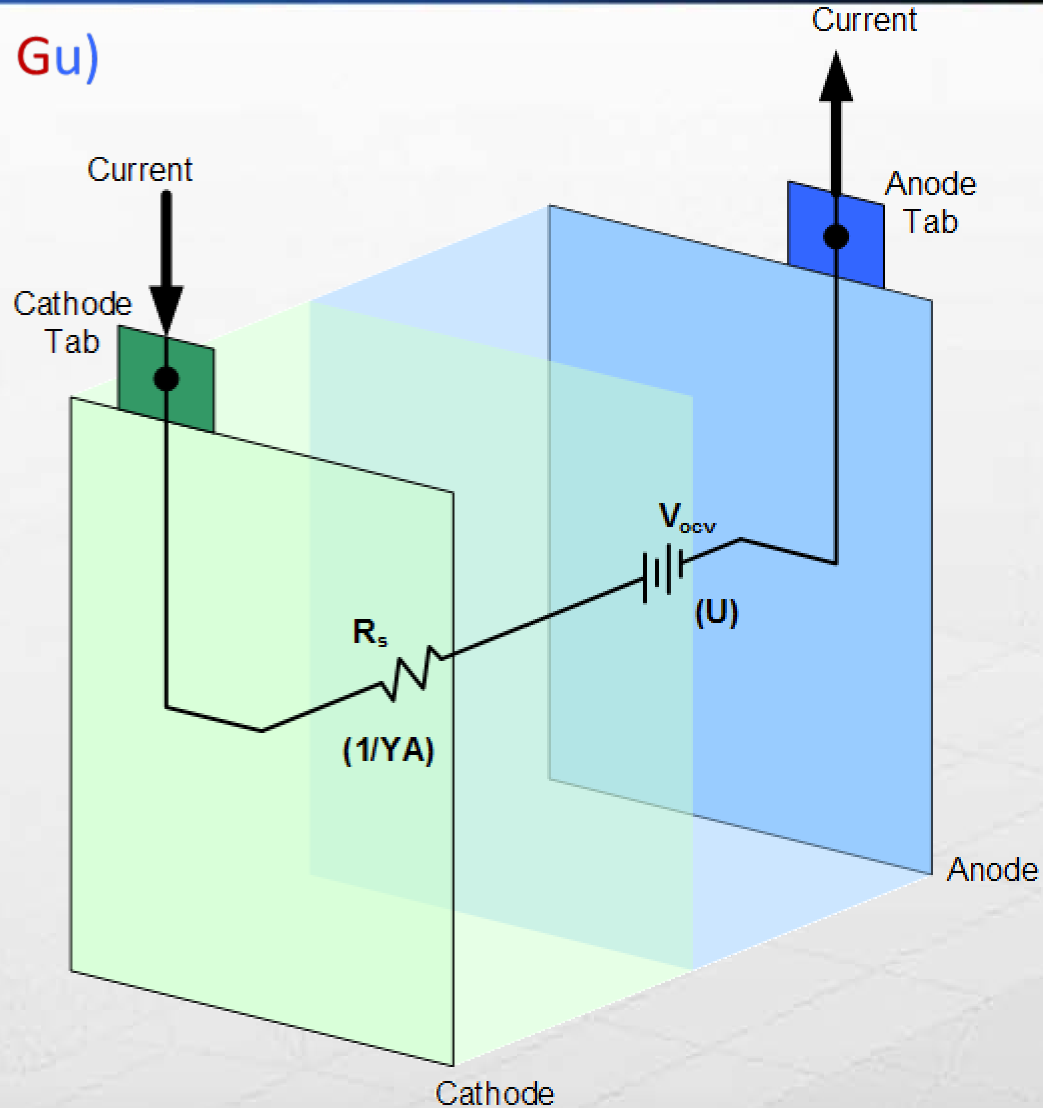
Battery Model Basics

- Electrical model
  - relates current transfer between electrodes to voltage difference across electrodes
- Resulting heat
  - applied to the thermal model



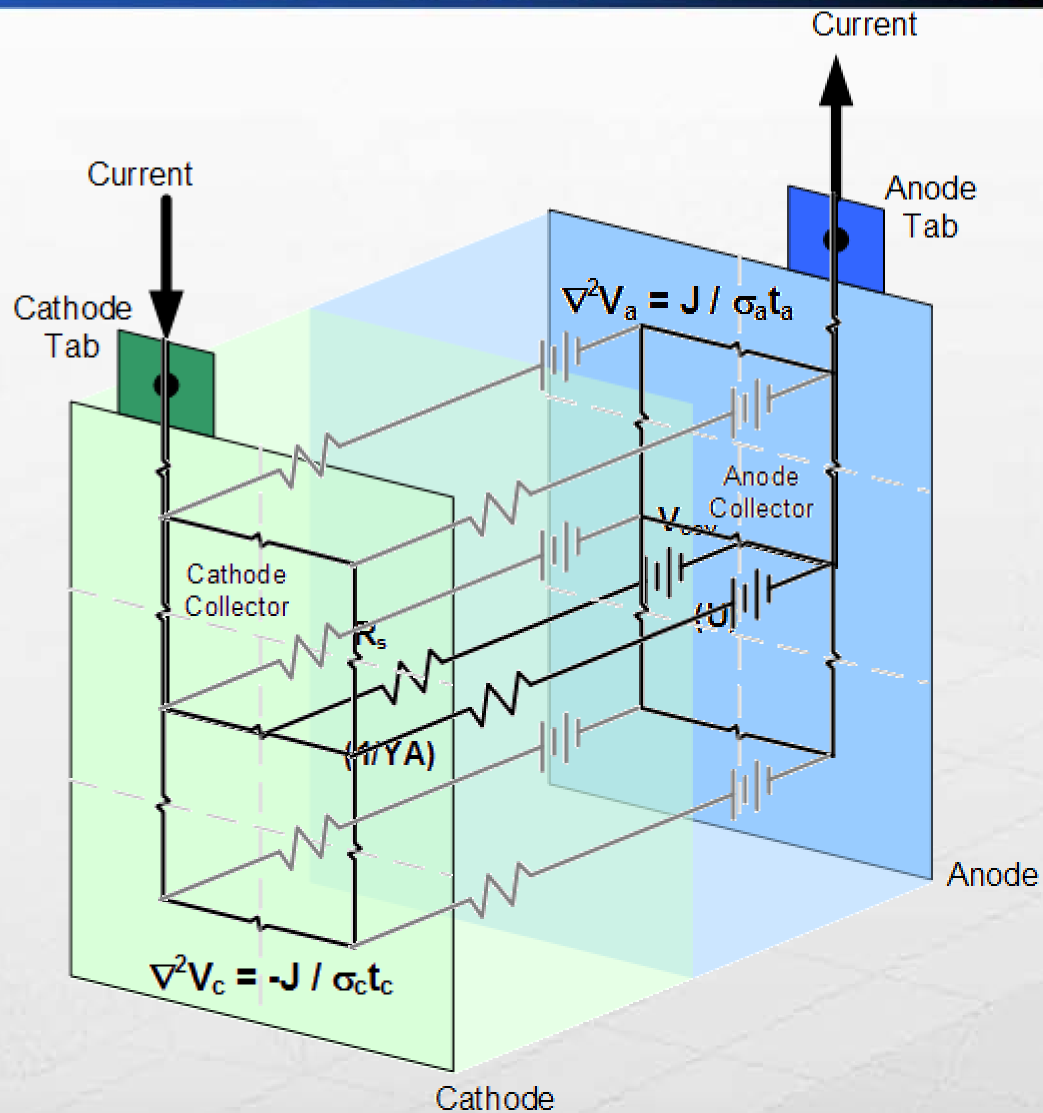
NTG Equivalent Circuit Model

- NTG (Newman, Tiedemann, and Gu)
- Electrical domain modeled with lumped parameter nodes
- Current-voltage characteristic for cell modeled as
  - $V_p - V_n = U + I/YA$
    - I = current
    - V_p = voltage on the positive electrode (cathode)
    - V_n = voltage on the negative electrode (anode)
    - U = 'open cell voltage'
      - $= f(DoD, T)$
    - Y = 'cell conductance'
      - $= g(DoD, T)$
    - $\dot{Q} = I^2/YA + ITdU/dT$
    - Applied uniformly over cell

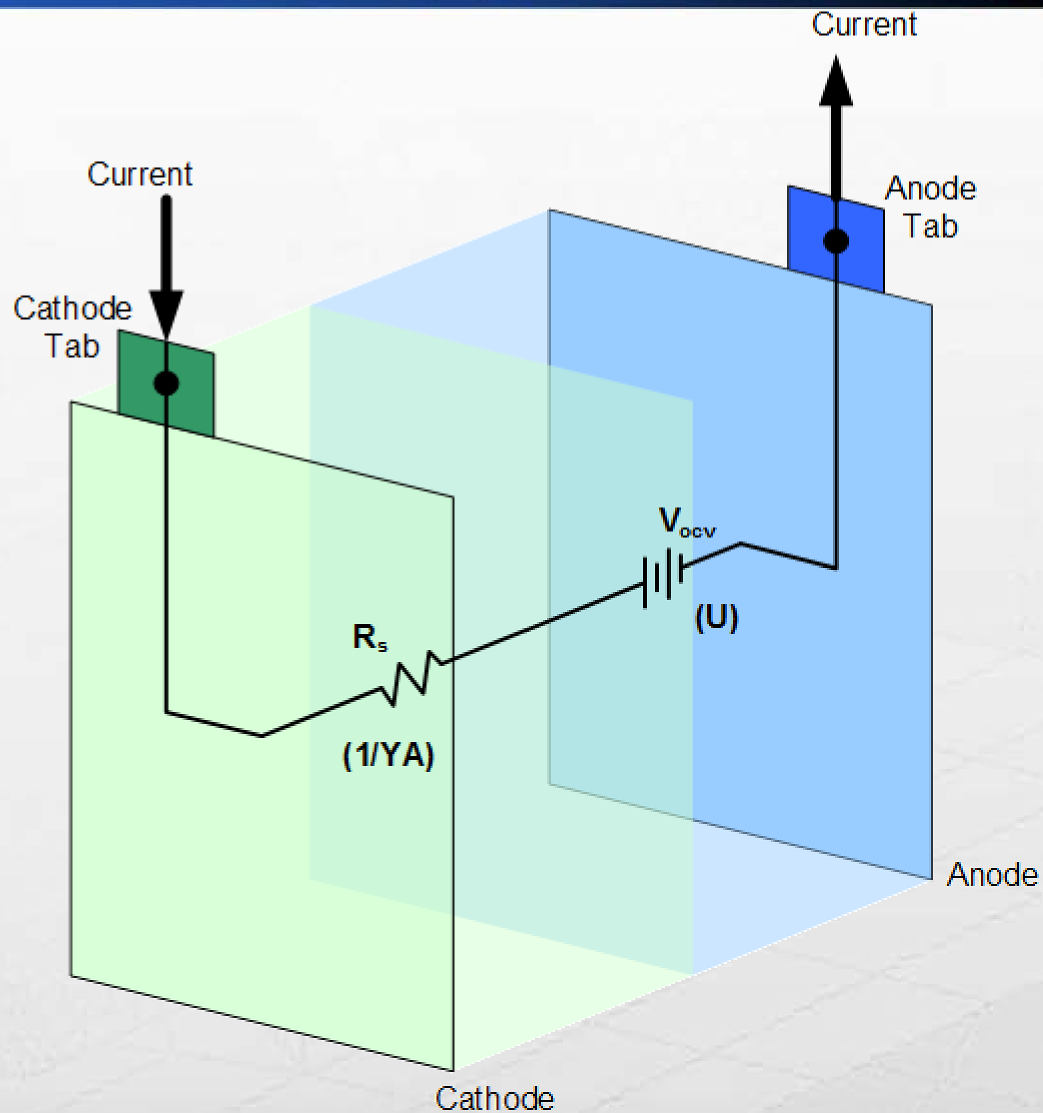


NTG Distributed Model

- Electrical domain modeled with geometric mesh
  - Collector plates
- NTG current-voltage characteristic applied between each element pair in electrodes
- Local current density
- Local depth of discharge
- Local parameters (U, Y)
- Local heating
- Voltage distribution on collector plates



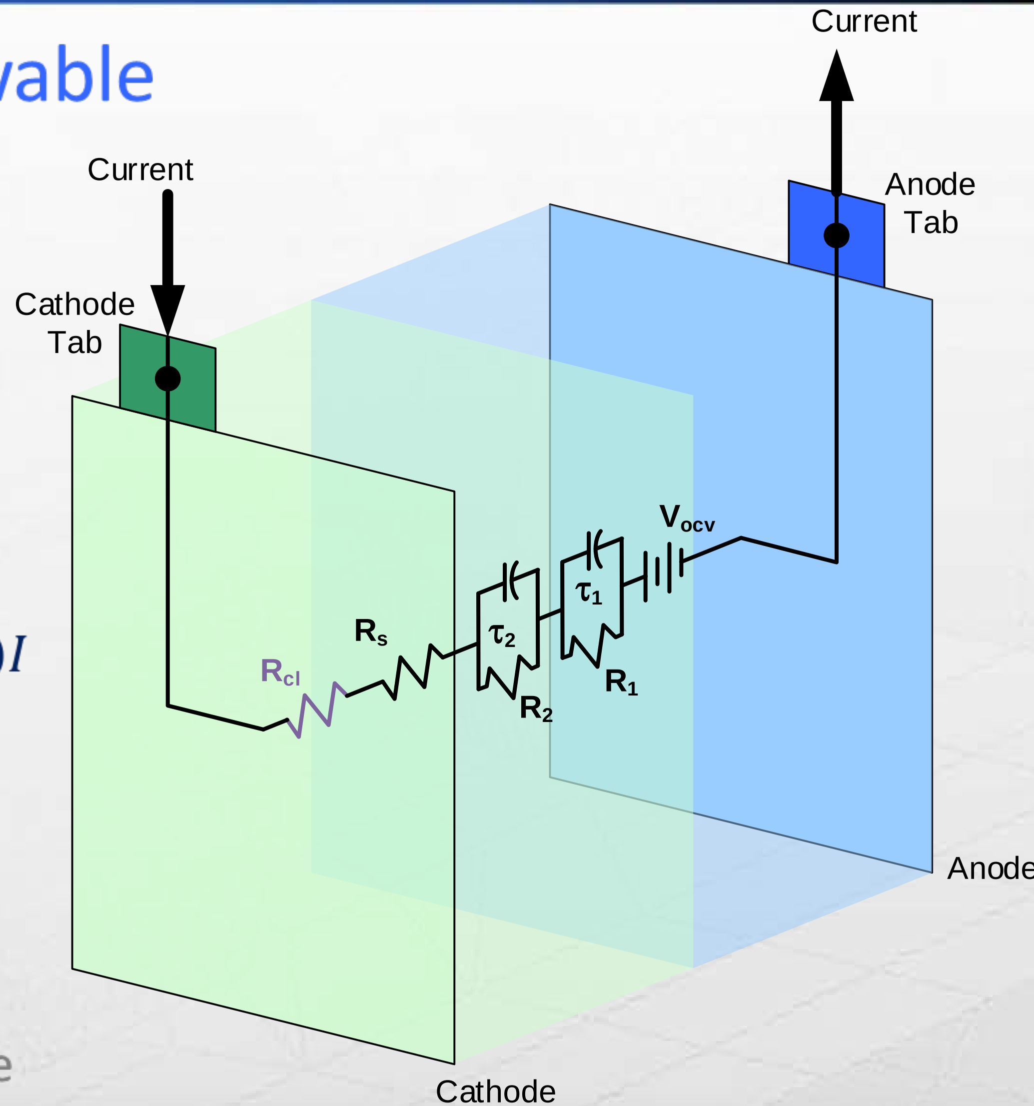
Back to equivalent circuit model…



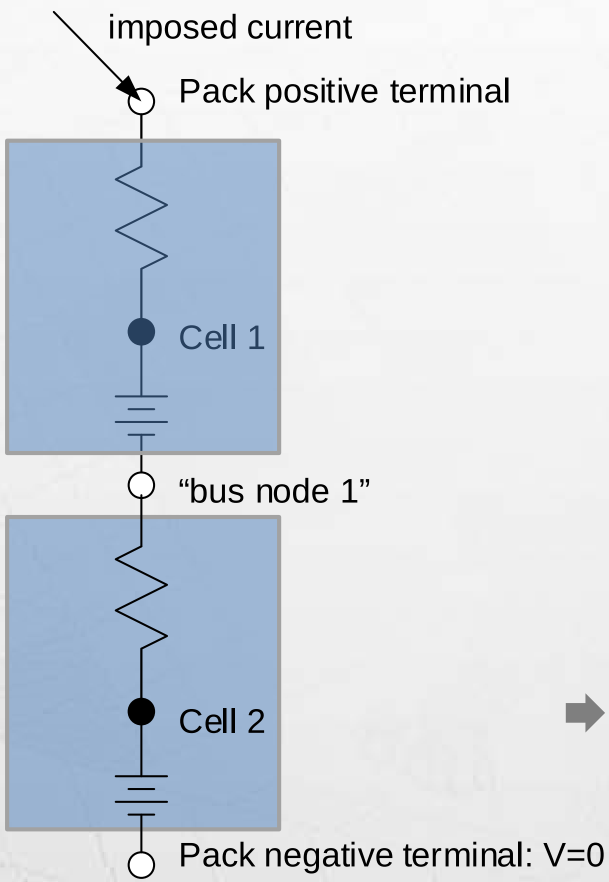
NREL Equivalent Circuit

- NREL (National Renewable Energy Laboratory)

- Current-voltage characteristic for cell modeled as
  - $V_t = V_{ocv} + \sum \Delta V_i + (R_s + R_{cl})I$
    - I = cell current
    - V_t = terminal voltage
    - V_{ocv} = open cell voltage
    - ΔV_i = voltage drop across filter circuit
    - R_s = cell internal resistance
    - R_{cl} = optional current limiting resistor



‘Bus nodes’ Are Used to Connect Cells



- **Bus nodes are lumped capacitance nodes**
  - Voltage computed by solver so that current in equals current out
  - Total current at positive terminal is imposed
    - Bus node name required to be “packPositiveTerminal”
  - Voltage at pack negative terminal is set to zero
    - Bus node name required to be “packNegativeTerminal”
  - Other bus node names are arbitrary
  - Connections are identified in the config file
    - Each cell definition has a cathode bus and an anode bus, thus:
      - Cell 1 cathode bus = “packPositiveTerminal”
      - Cell 1 anode bus = “bus node 1”
      - Cell 2 cathode bus = “bus node 1”
      - Cell 2 anode bus = “packNegativeTerminal”
- **If a lumped capacitance part has the name of a bus node, it will be used by the solver**
  - Voltage, current appear in post-processor
    - Model diagnostics

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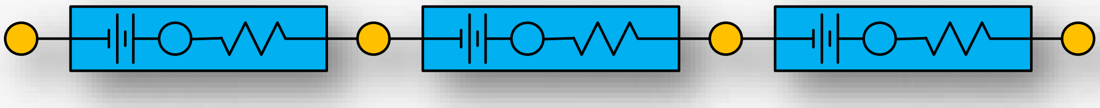
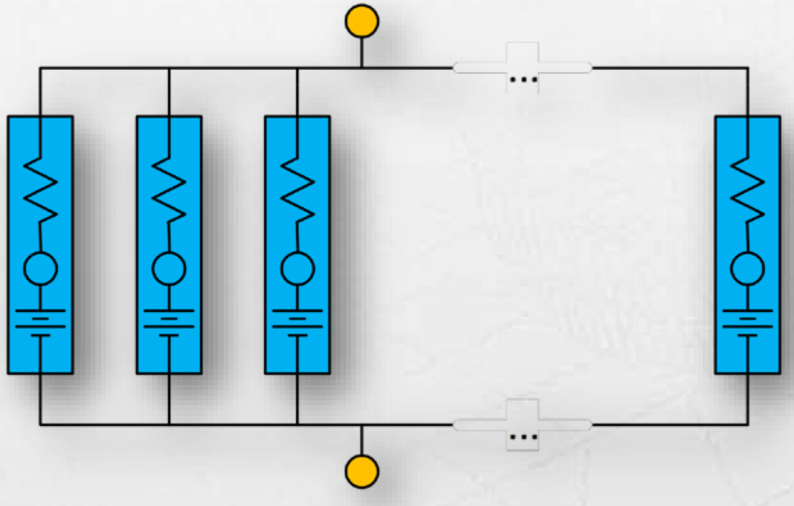
Cells Can Be Connected in Arbitrary Configurations

- Series



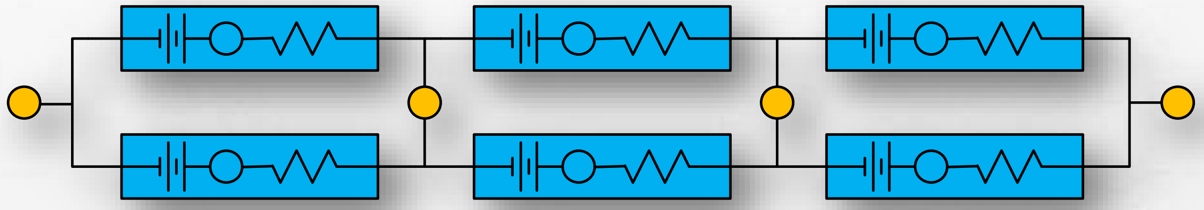
- Parallel



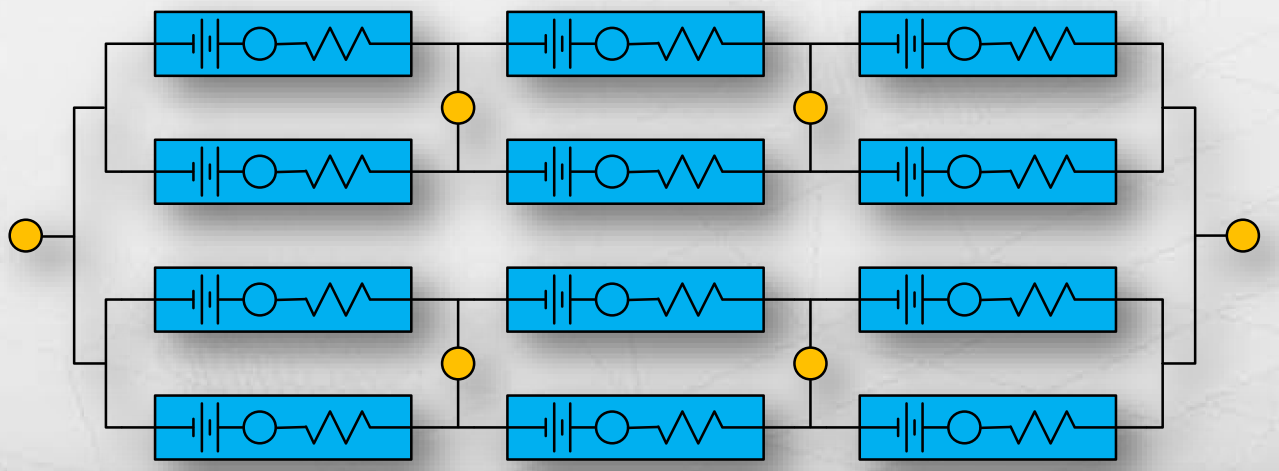
- Current distributions are found by adjusting node voltages until net current into node is zero

Cells Can Be Connected in Arbitrary Configurations

- Series / parallel combinations
  - Modules



  - Packs



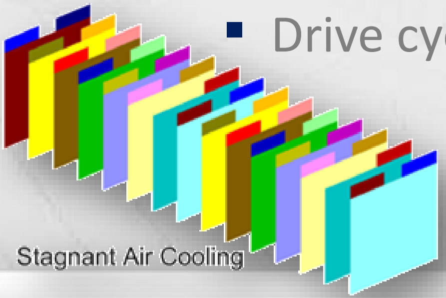
Comparison of Equivalent Circuit and Distributed Models

Equivalent Circuit

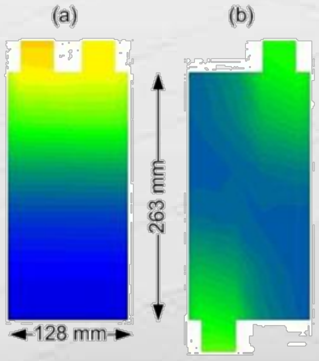
- Sacrifices detail for speed
- Appropriate for pack modeling
  - Cooling concept studies
  - Cell-to-cell variability
  - Fault conditions (shorts)
  - Drive cycle analyses

Distributed Model

- Sacrifices speed for detail
- Most appropriate for cell modeling
  - Cell size / aspect ratio
  - Tab size / location
  - Hot-spot analysis
  - Uniformity of utilization of active material



Can be used together



Comparison of Models

	NTG Distributed	NTG Equiv. Circuit	NREL Equiv. circuit
Voltage distribution on electrode	Computed	NA	NA
Cell heating	Applied locally on electrodes	Applied uniformly to cell mass	Applied uniformly to cell mass
Temperature distribution on electrode	Computed locally from local heating	Computed locally from global heating	Computed locally from global heating
Cell to cell variation of parameters	Not allowed	Yes	Yes
Pack circuit topology	Possible, connections must be meshed	Yes, connections created virtually	Yes, connections created virtually
Charge carrier depletion	DoD computed locally	DoD computed for cell	DoD computed for cell
Transient voltage effects	No	No	Yes
Fault analysis	Possible, but very cumbersome	Possible, but cumbersome	Yes
Cell parameter inputs	U, Y, constant dU/dT	U, Y, constant dU/dT	Functional Rs, R_i's, t's, Rcl, dU/dT
Circuit topology inputs	None	List of connections	List of connections
Compute time	Longer	Shorter	Shorter
Mesh size	Larger	Smaller	Smaller

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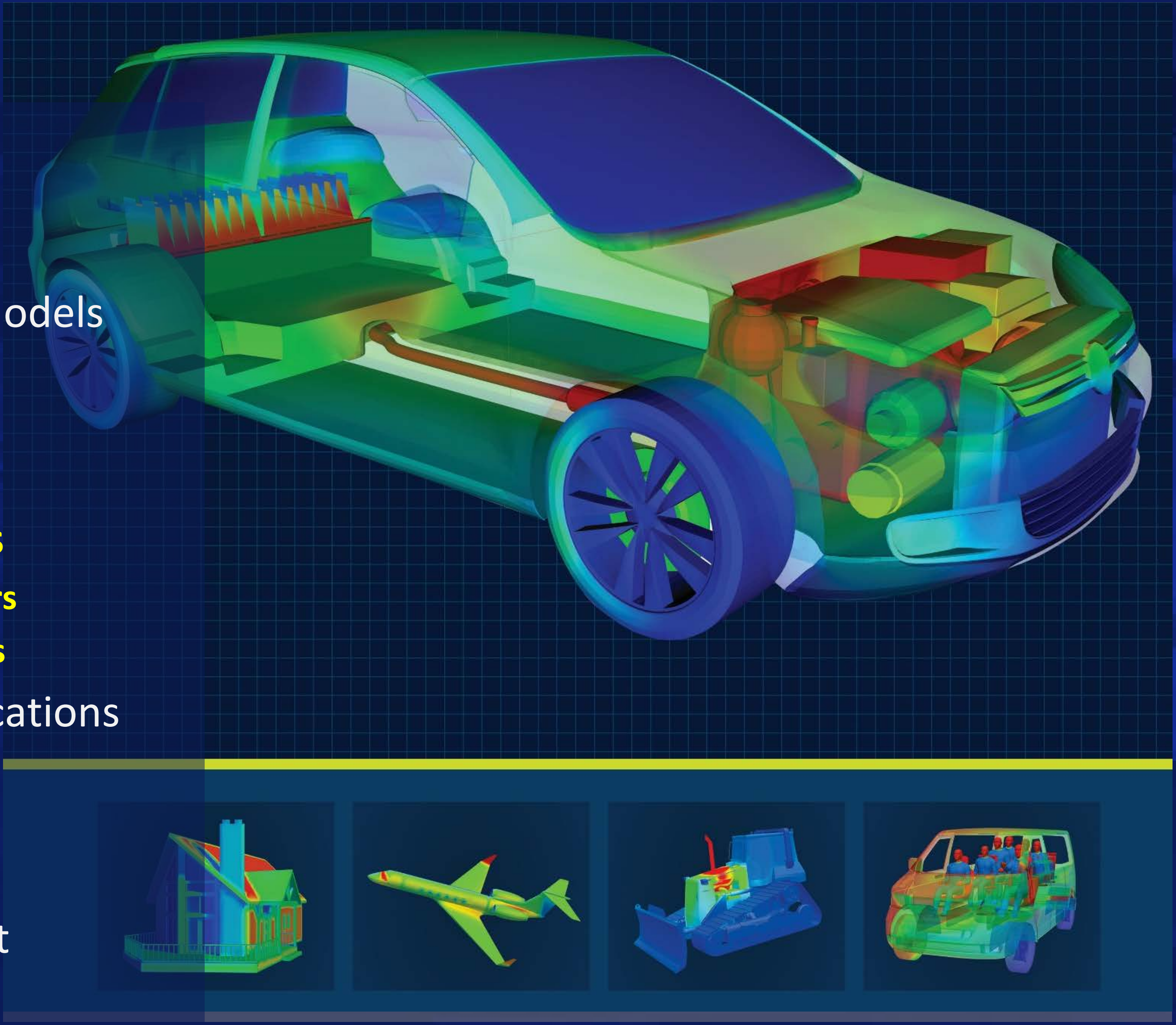


Data Needed for Input to Models

- Readily available from supplier:
  - Cell capacity, electrode area
- Available from supplier or measured by user:
  - Discharge curves at different C-rates or pulse profiles
    - voltage versus depth-of-discharge
    - sufficient to resolve curve at beginning & end of discharge
- Difficult to obtain from supplier:
  - Cell material properties
    - material thicknesses
    - material properties
      - (density, specific heat, conductivity)

Battery Model Inputs

NTG equiv. circuit	NTG distributed	NREL equiv. circuit
$U\ (= f[DoD,T])$	$U\ (= f[DoD,T])$	$V_{ocv}\ (= f[DoD,T])$
$Y\ (= g[DoD,T])$	$Y\ (= g[DoD,T])$	$R_s\ (= g[DoD,T])$
		$R_i\ (= r[DoD,T])$
		$\tau_i\ (= t[T])$
$dU_{oc}/dT\ (= \text{constant})$	$dU_{oc}/dT\ (= \text{constant})$	$dU_{oc}/dT\ (= u[DoD,T])$
Bus node list	*	Bus node list
Current	*	Current
Cell list	*	Cell list
Anode bus	*	Anode bus
Cathode bus	*	Cathode bus
Initial DoD	Initial DoD	Initial DoD
Electrode area	*	Electrode area
Cell capacity	Cell capacity / area	Cell capacity
	Anode/Cathode conductivity	

* Implied or derived from model/geometry set-up

Battery Model Parameters are Obtained From Cell Discharge Data

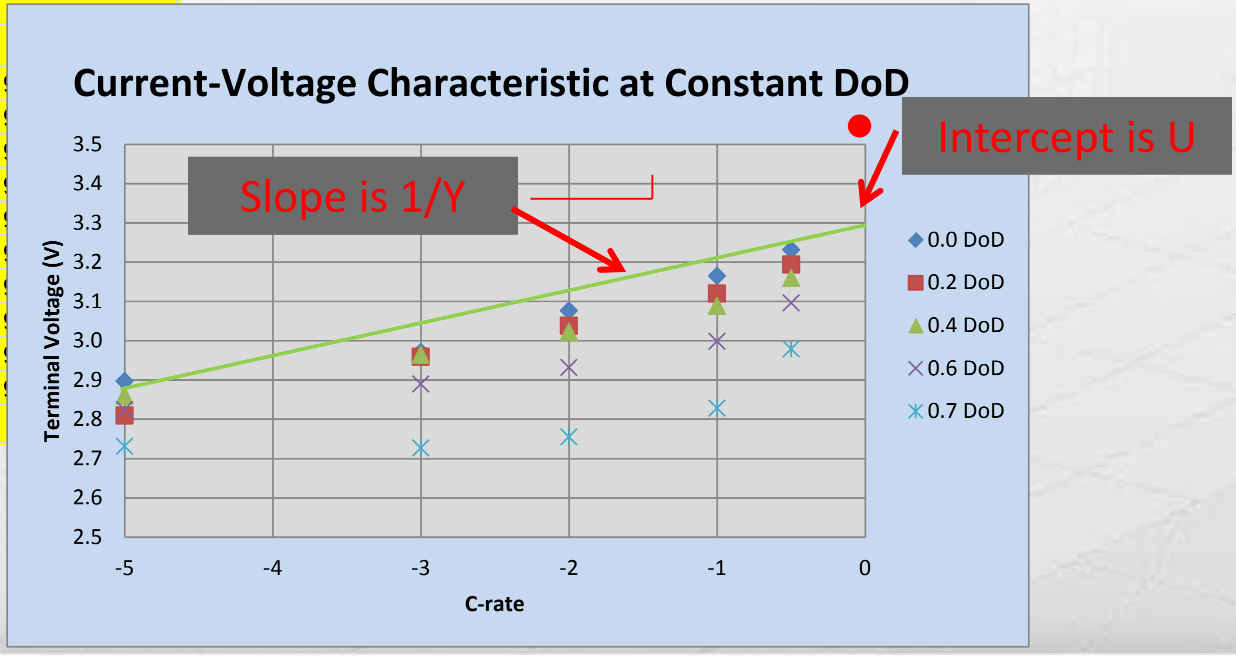
- NTG parameters
  - derived from curves of voltage vs time for constant charge or discharge
- NREL parameters
  - derived from curves of voltage vs time during prescribed current pulses at (approximately) constant DoD

Up to now, the discussion has been independent of battery chemistry. The parameter values determined by the chemistry for a particular cell.

NTG Coefficients Derived from Voltage Curves at Constant Current for Different Discharge Rates

- $J = Y(\Delta V - U)$
- Consider V as a function of C-rate (current density) at different values of DoD:
  - Current density = C_{rate} * capacity / area
- Fit a line through the data at constant DoD

	C-rate			
DoD	-0.5	-1	-2	-3
0.01	3.232	3.165	3.076	2.
0.02	3.221	3.139	3.055	2.
0.04	3.215	3.130	3.039	2.
0.06	3.213	3.127	3.034	2.
0.08	3.210	3.127	3.033	2.
0.10	3.208	3.127	3.034	2.
0.12	3.206	3.126	3.035	2.
0.14	3.203	3.125	3.036	2.
0.16	3.201	3.123	3.037	2.
0.18	3.197	3.121	3.038	2.
⋮	⋮	⋮	⋮	



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NREL Coefficients Obtained from Voltage Measurements During Pulsed Current Test Profile

- Hybrid Pulse Power Characterization (HPPC) test as specified in "FreedomCAR Battery Test Manual For Power-Assist Hybrid Electric Vehicles" (DOE/ID-11069, published October 2003)
  - Fixed duration current charge / discharge cycles at successive increasing values of DoD

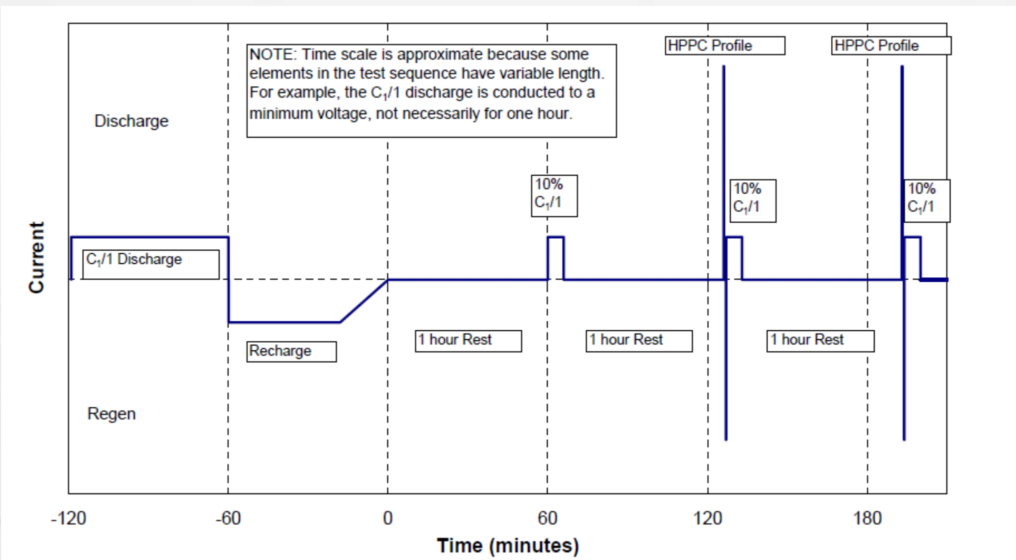
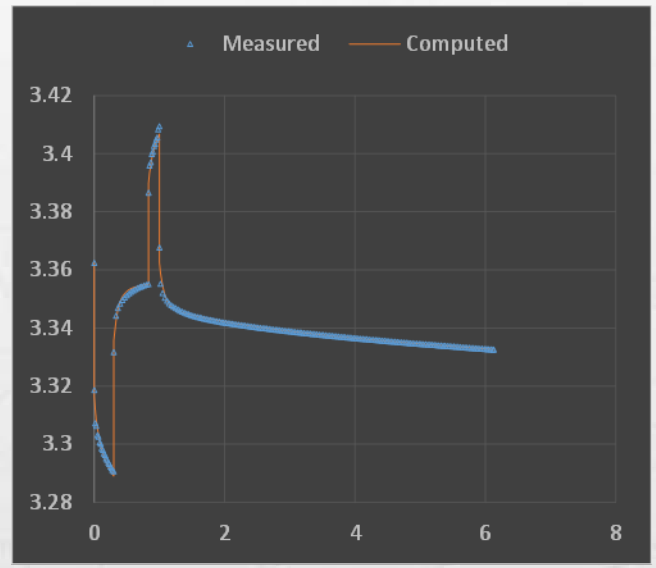


Figure 2. Hybrid Pulse Power Characterization Test (start of test sequence).



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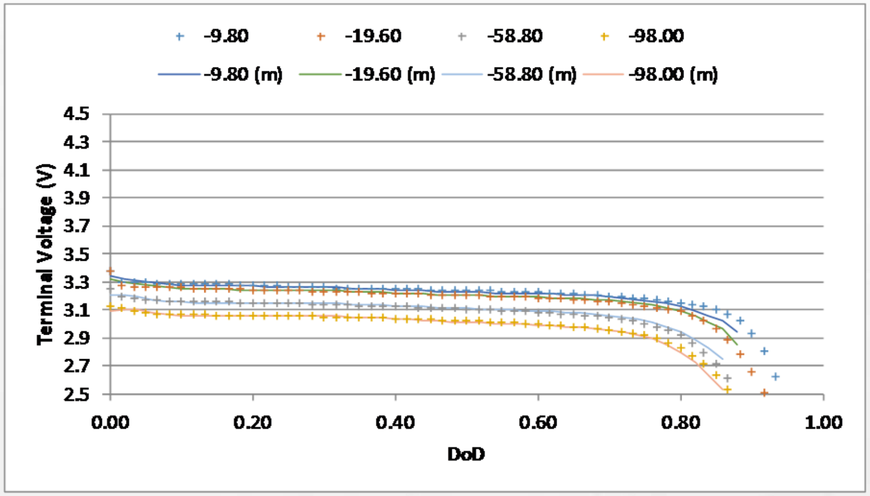
TAI is Developing a Tool to Simplify Battery Parameter Generation From Test Data

Plot data for temperature of 25 C

Plot model voltage prediction



Temperature is defined as: ambientTemp

Write parameter definition to file...

Show U parameter

Show Y parameter

Curvefit coefficients

Order of DoD fit: 5

Plot Y coefficients vs T

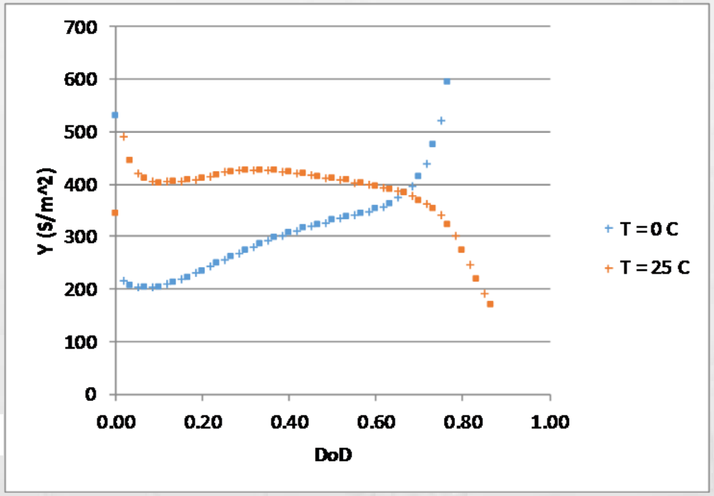
Coefficient selector: All

Order of T fit: 0

Tabular data

Uniform spacing every 2 points

Select points by picking on plot



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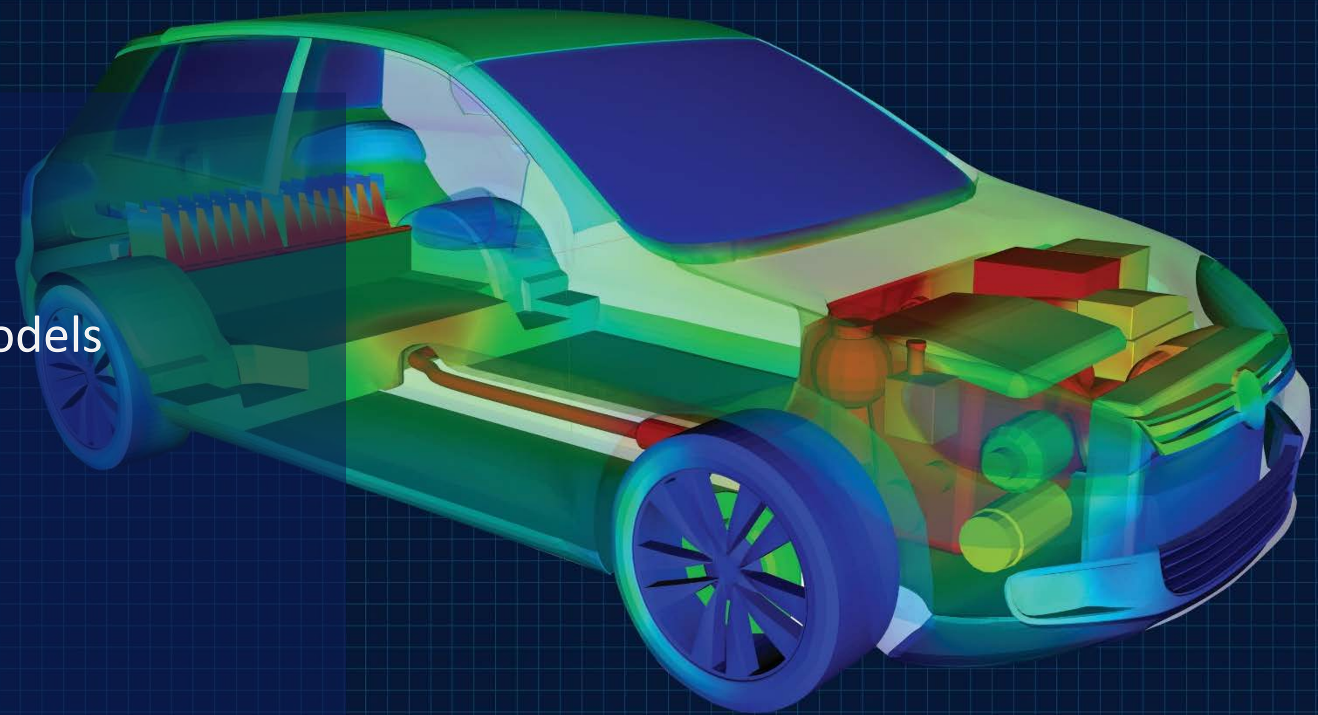

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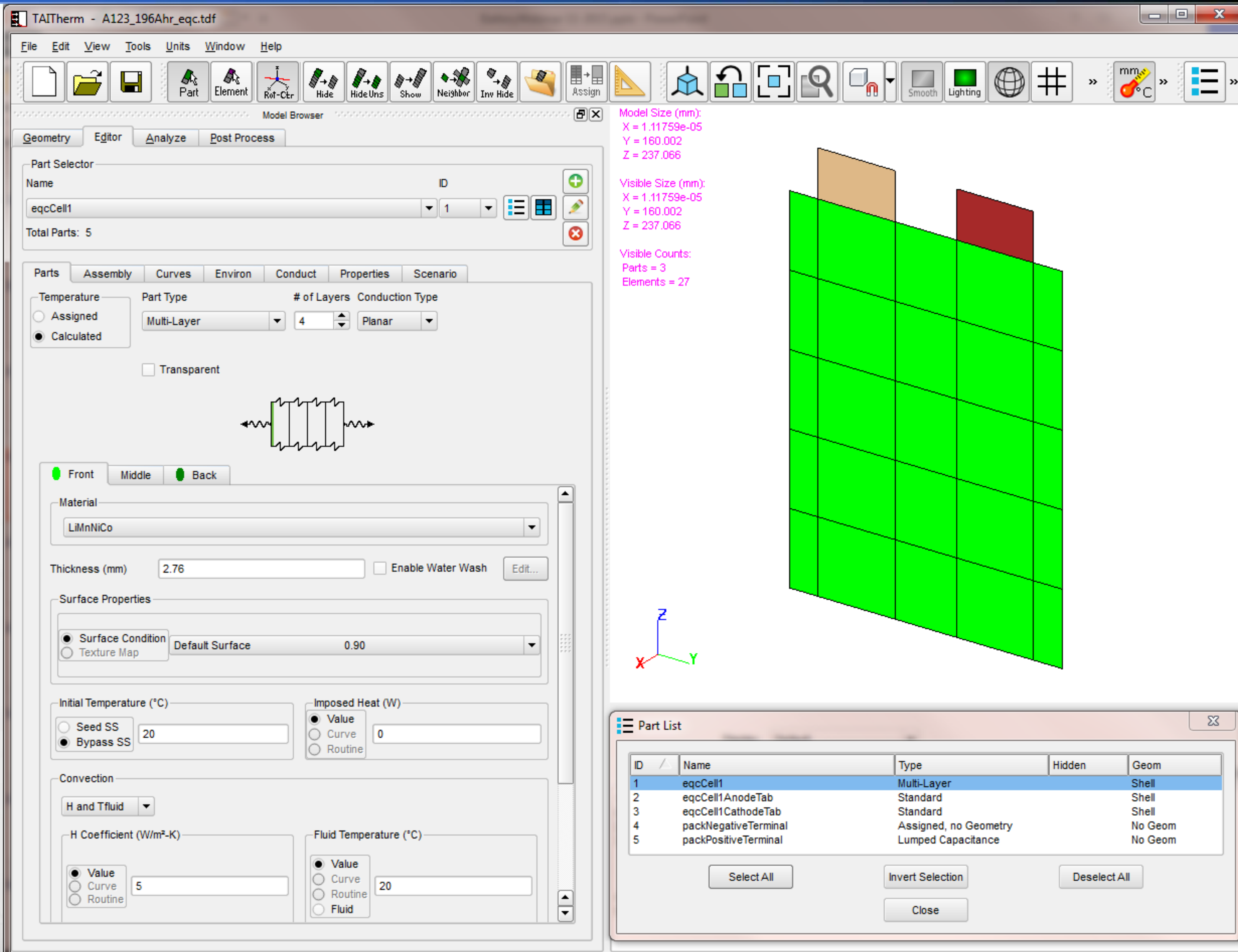
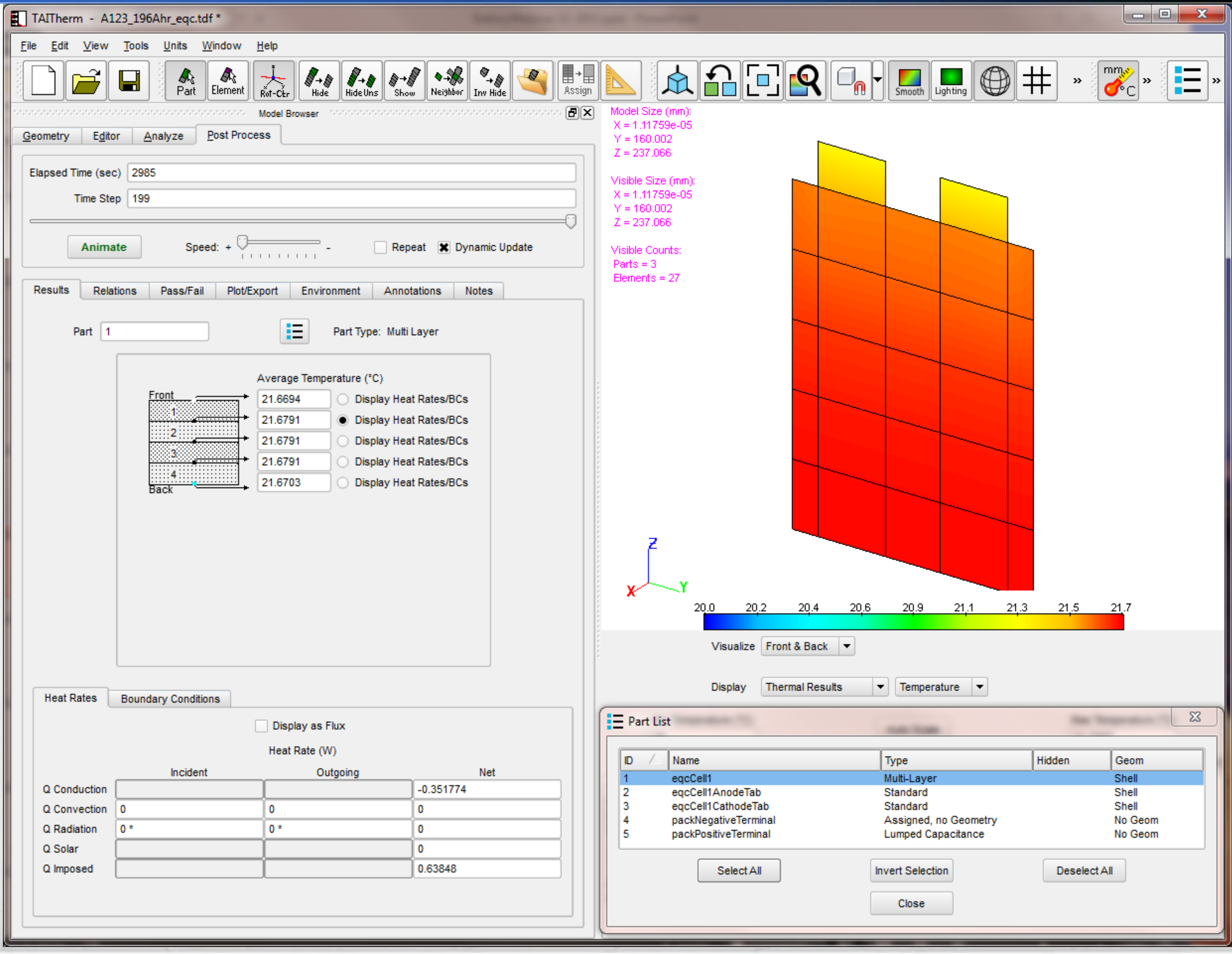
NTG Equivalent Circuit Model – Single Cell

- Thermal domain modeled with mesh
- Electrical domain modeled with lumped capacitance nodes created virtually
- Part naming convention links electrical and thermal domains
- No restrictions on thermal boundary conditions



NTG Equivalent Circuit Model – Single Cell

- Thermal results show temperature distribution



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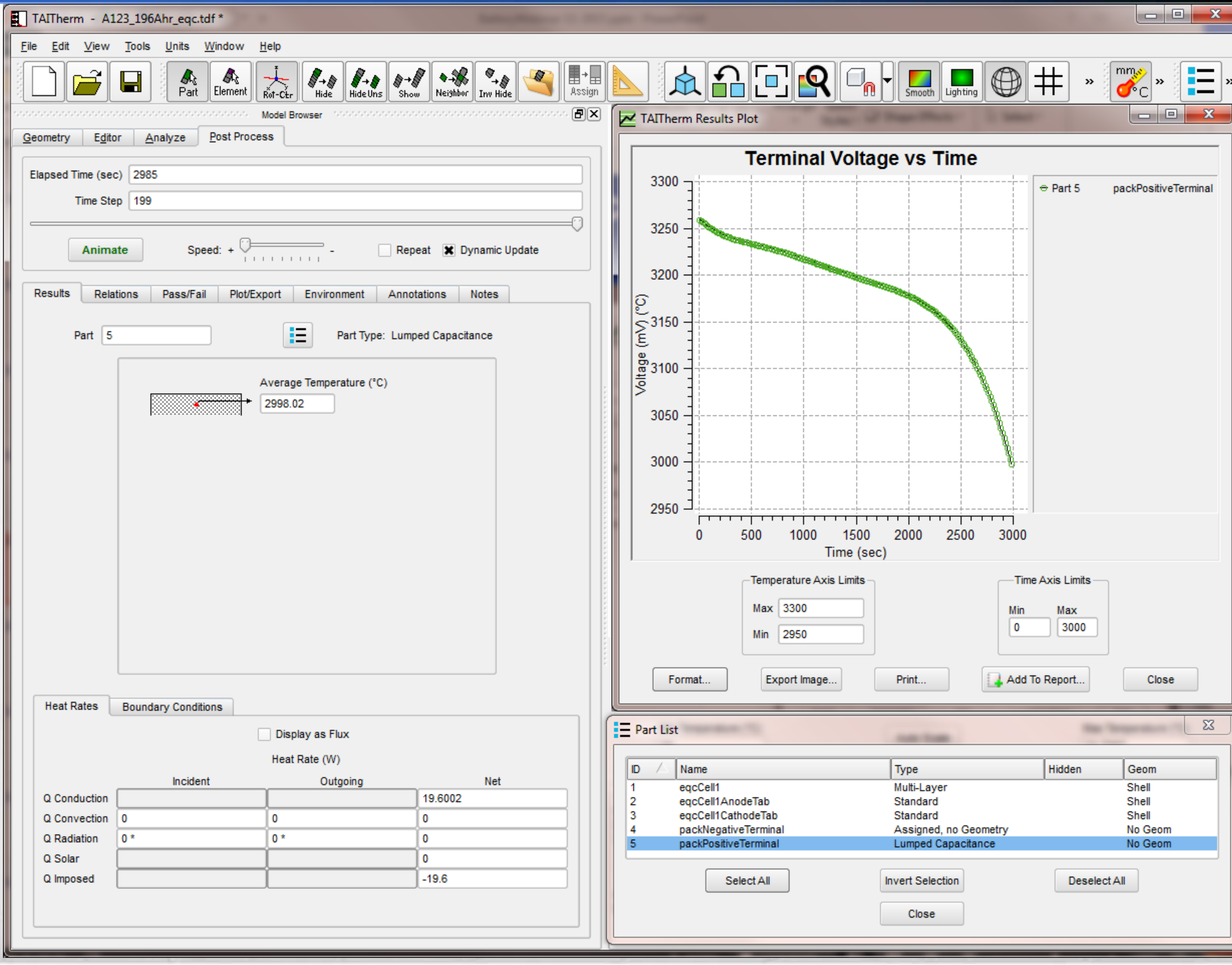
NTG Equivalent Circuit Model – Single Cell

- Electrical results are also available in post-processor



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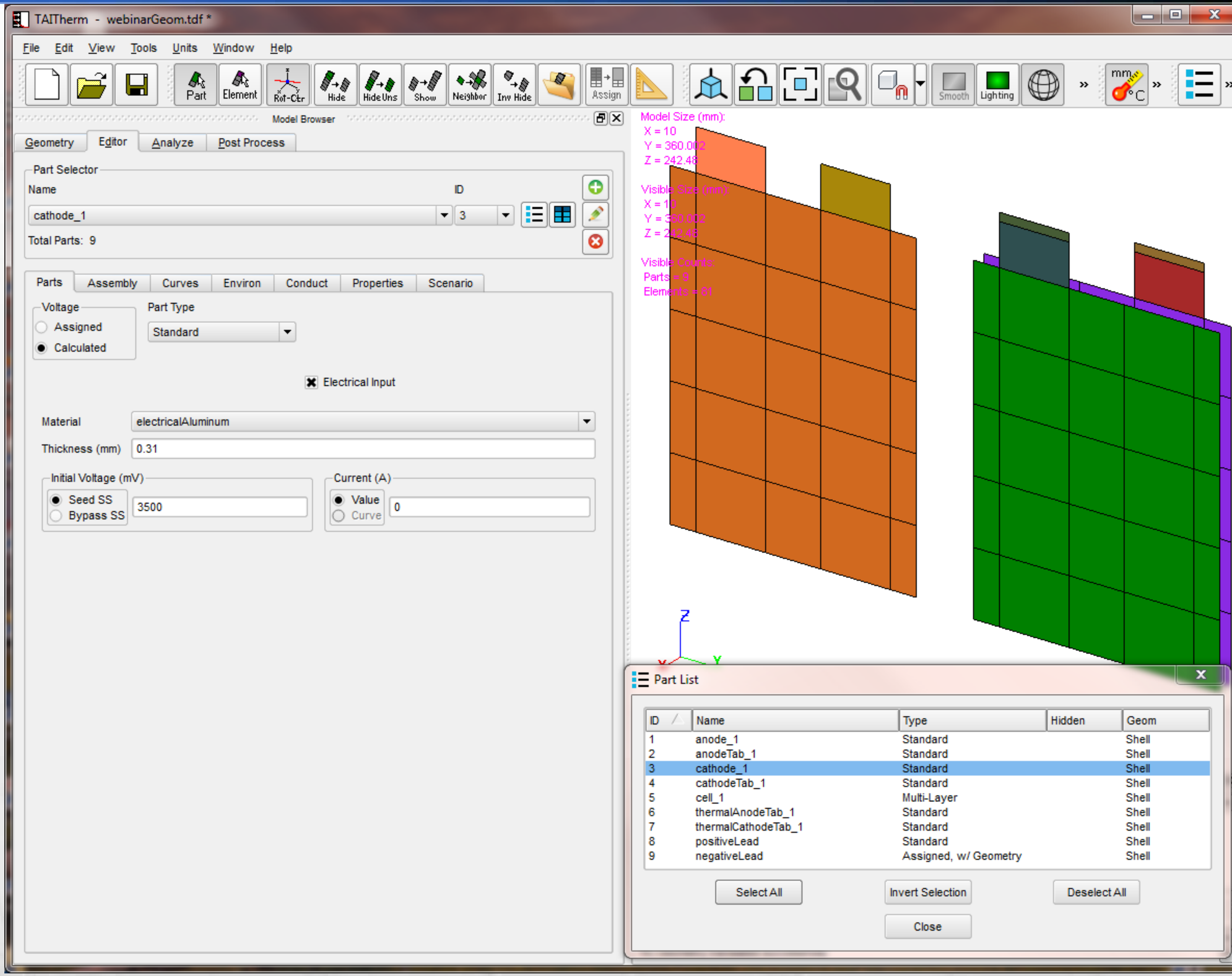
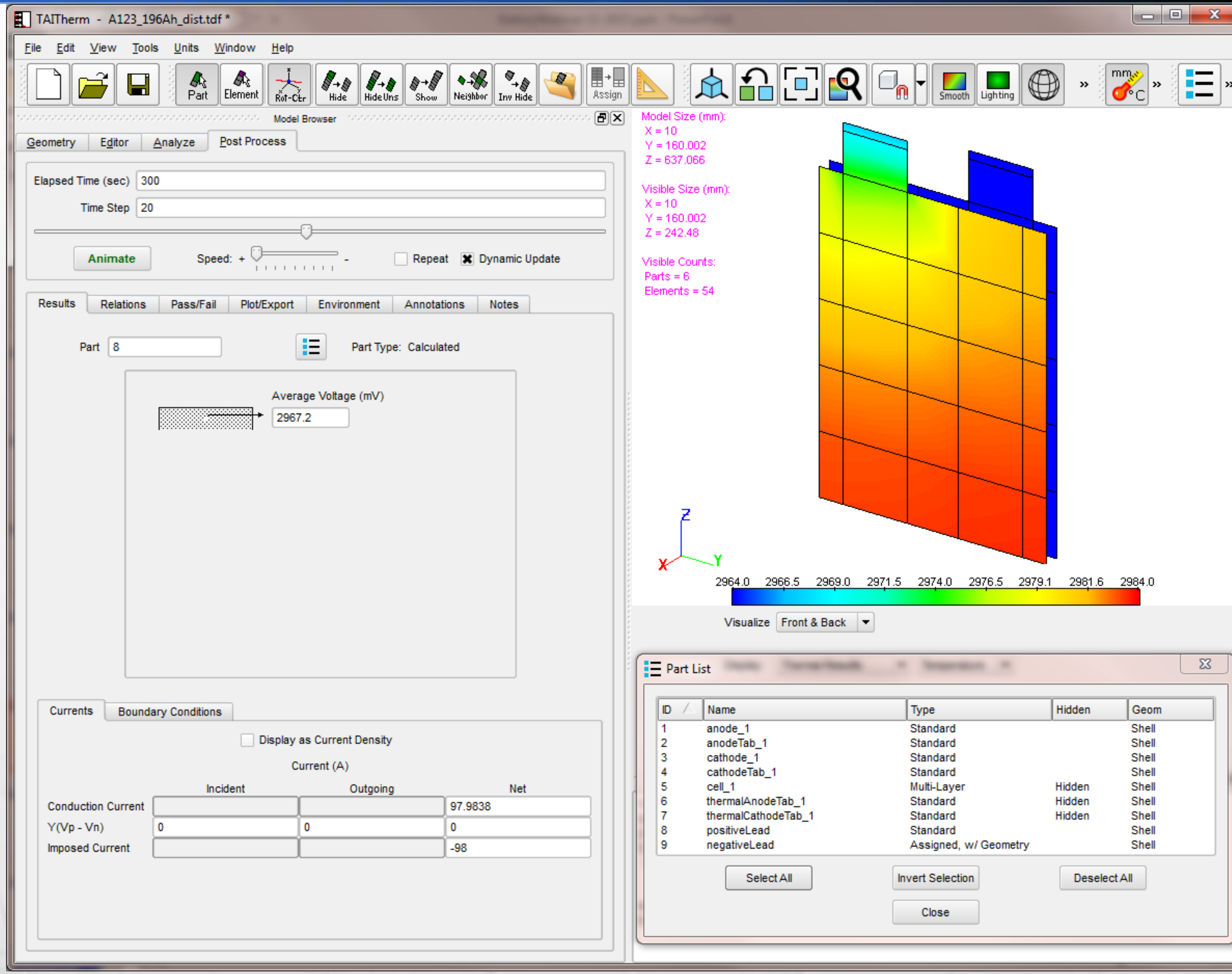
NTG Distributed Model – Single Pouch Cell

- Distributed model employs a mesh for the thermal *and* the electrical domain
  - Separate parts for cathode and anode
- Part naming convention links electrical and thermal domains



NTG Distributed Model – Single Pouch Cell

- Voltage distribution is rendered in the post-processor



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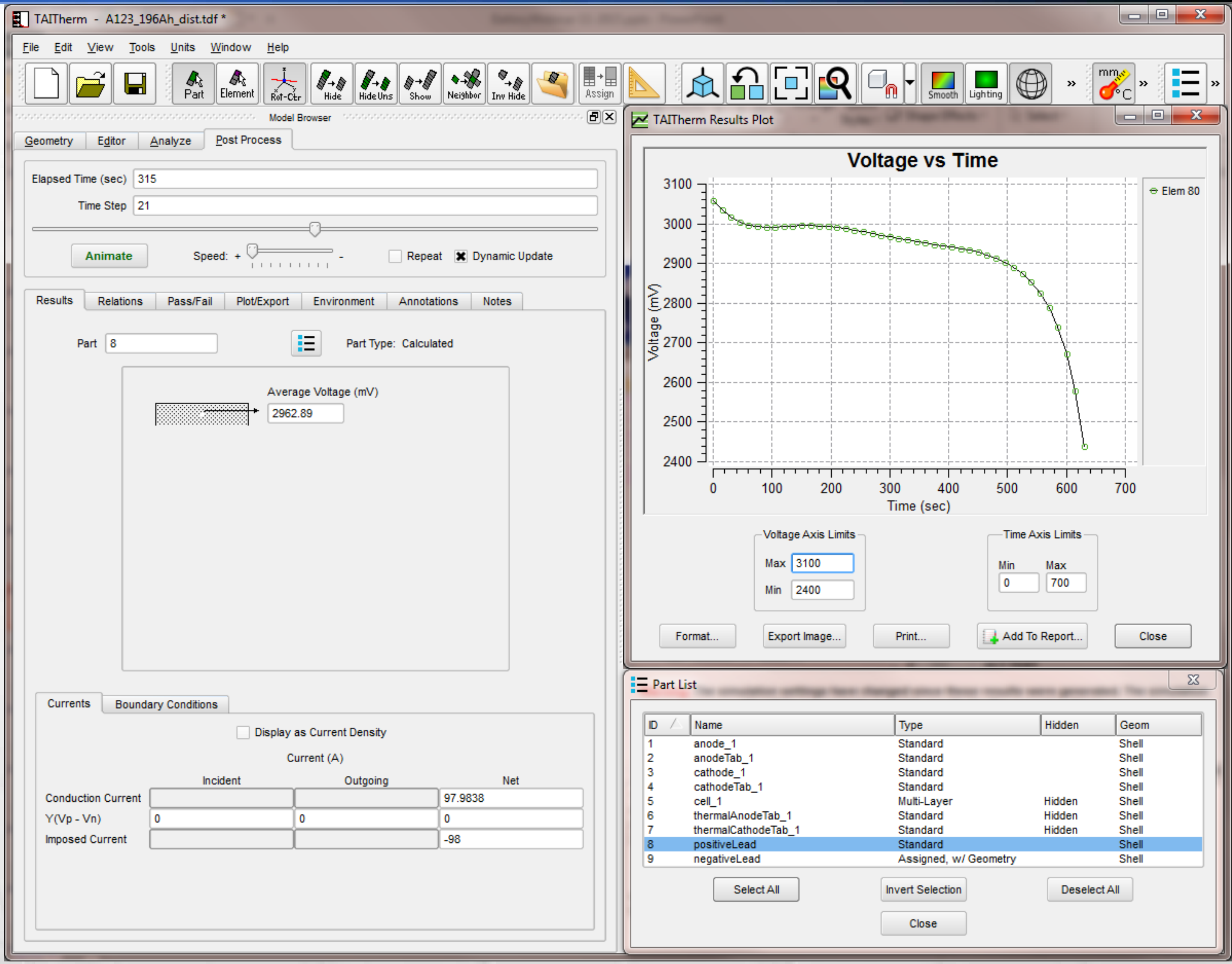
NTG Distributed Model – Single Pouch Cell

- Time plots of terminal voltage are available as well



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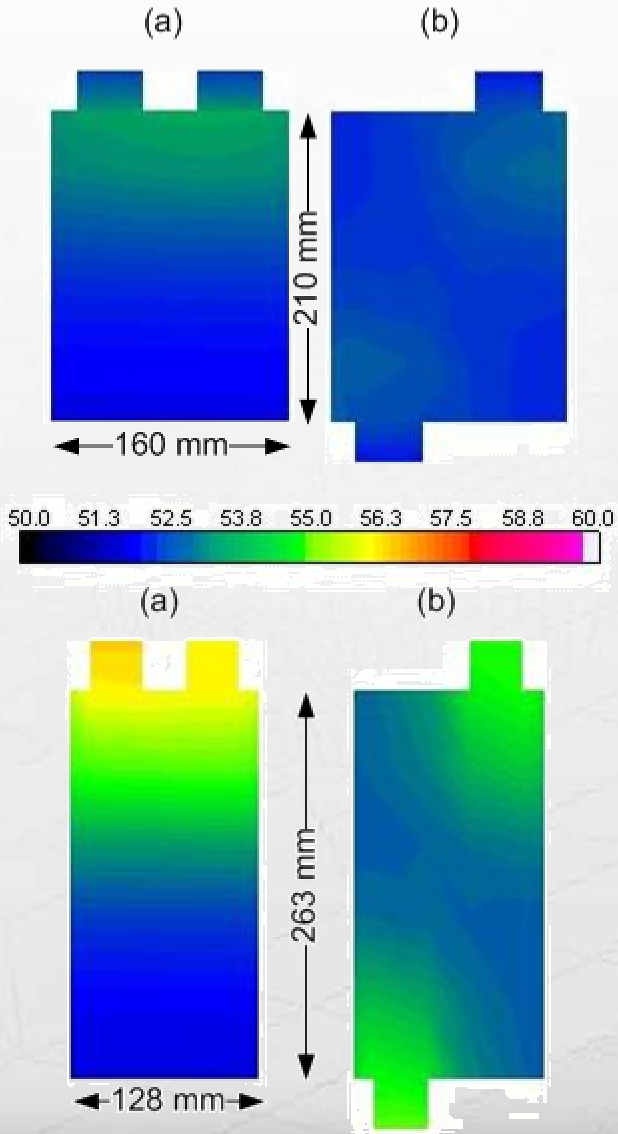
NTG Distributed Model Applications

- Effects of tab size/location, cell size, collector thickness:
  - Voltage gradients on collector plates
  - Non-uniform current density
  - Non-uniform ion depletion
  - Non-uniform heating



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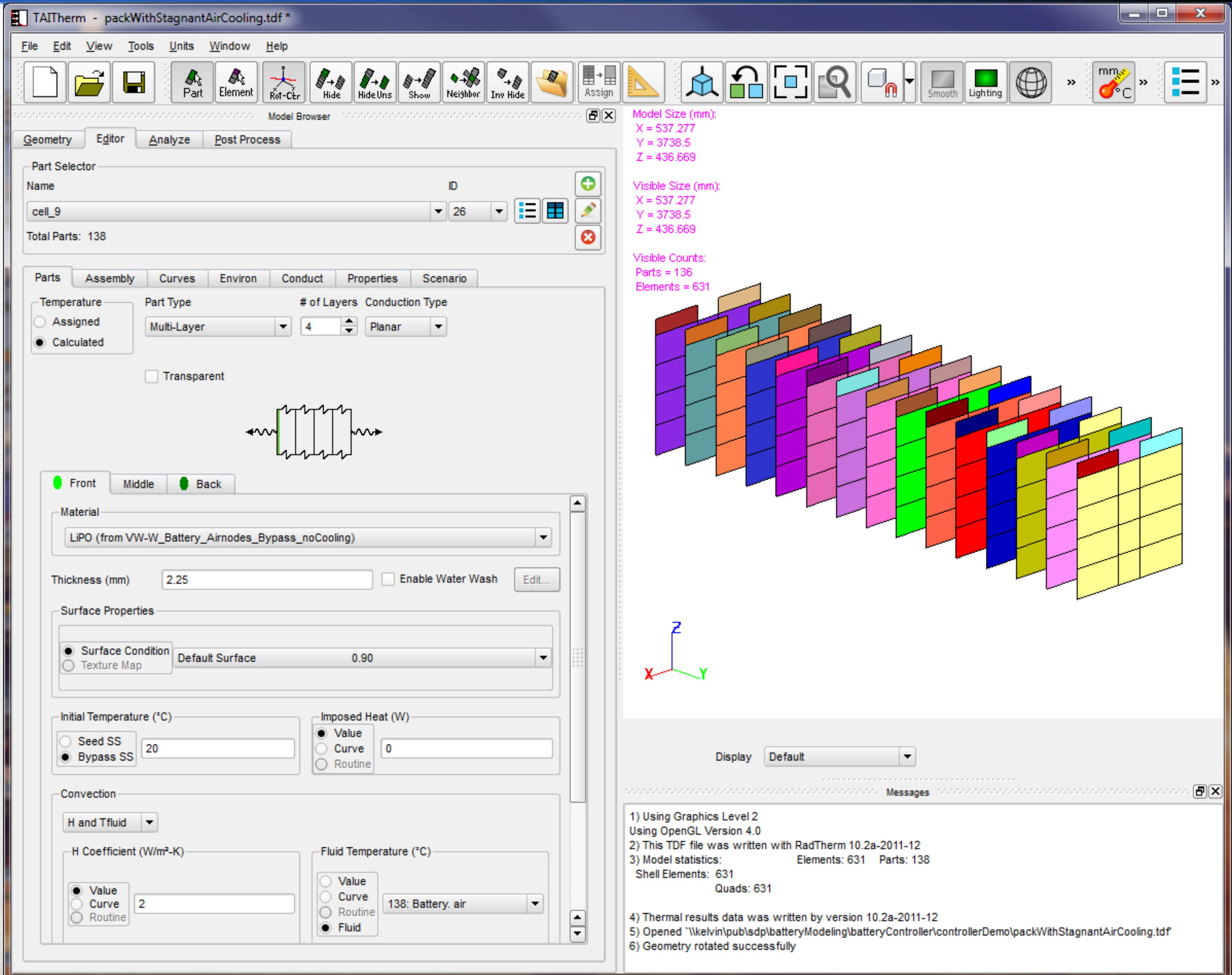
NTG Equivalent Circuit Model – Pack with Different Cooling Concepts

- Modules or packs are modeled as groups of individual cells

- Effect of cooling strategies can be investigated



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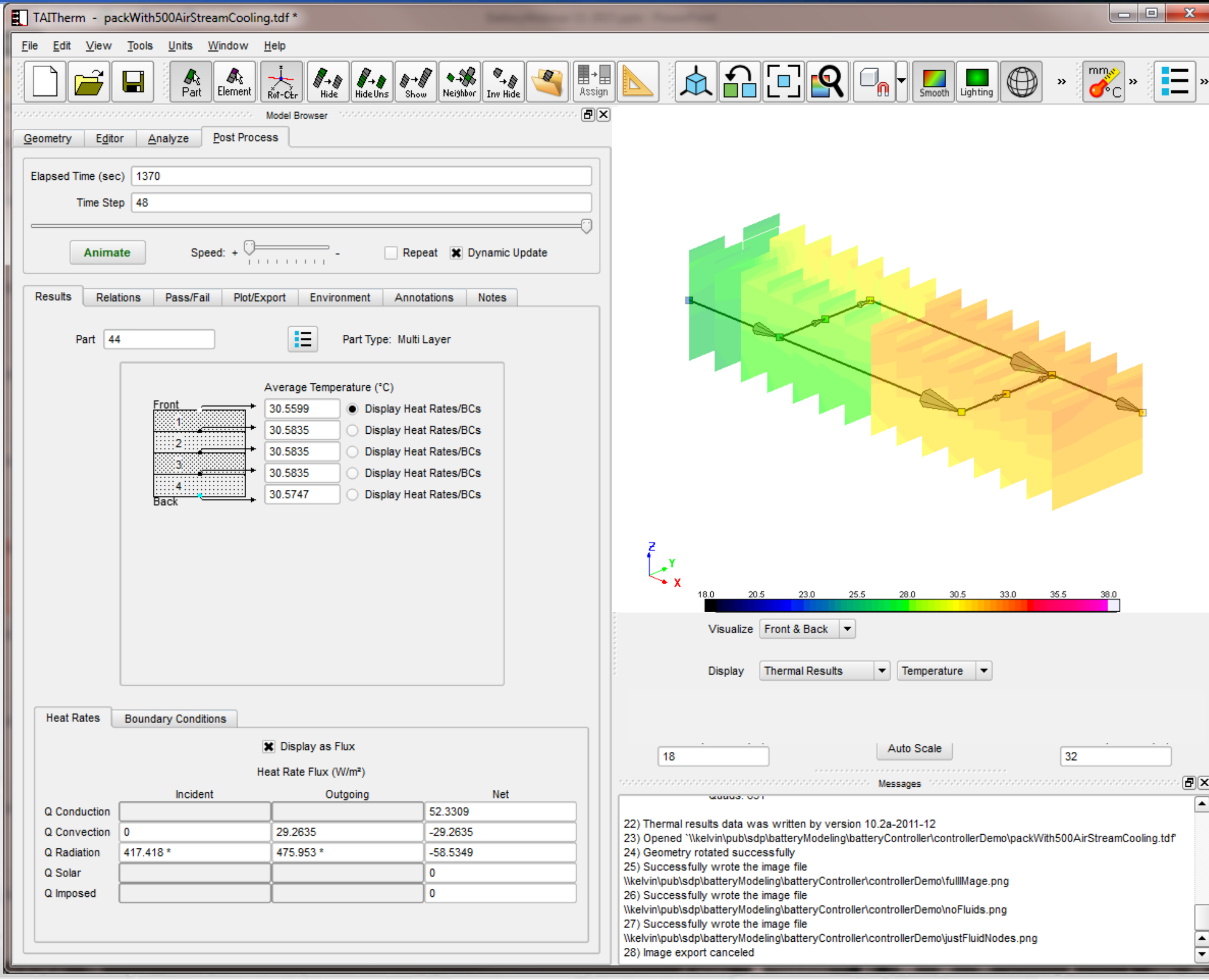
NTG Equivalent Circuit Model – Pack with Different Cooling Concepts

- Case with air forced through pack at various flow rates
- Advection links between fluid nodes models coupling to fluid flow
- Provides quick alternative to coupled CFD
- Investigate non-uniform cooling in pack



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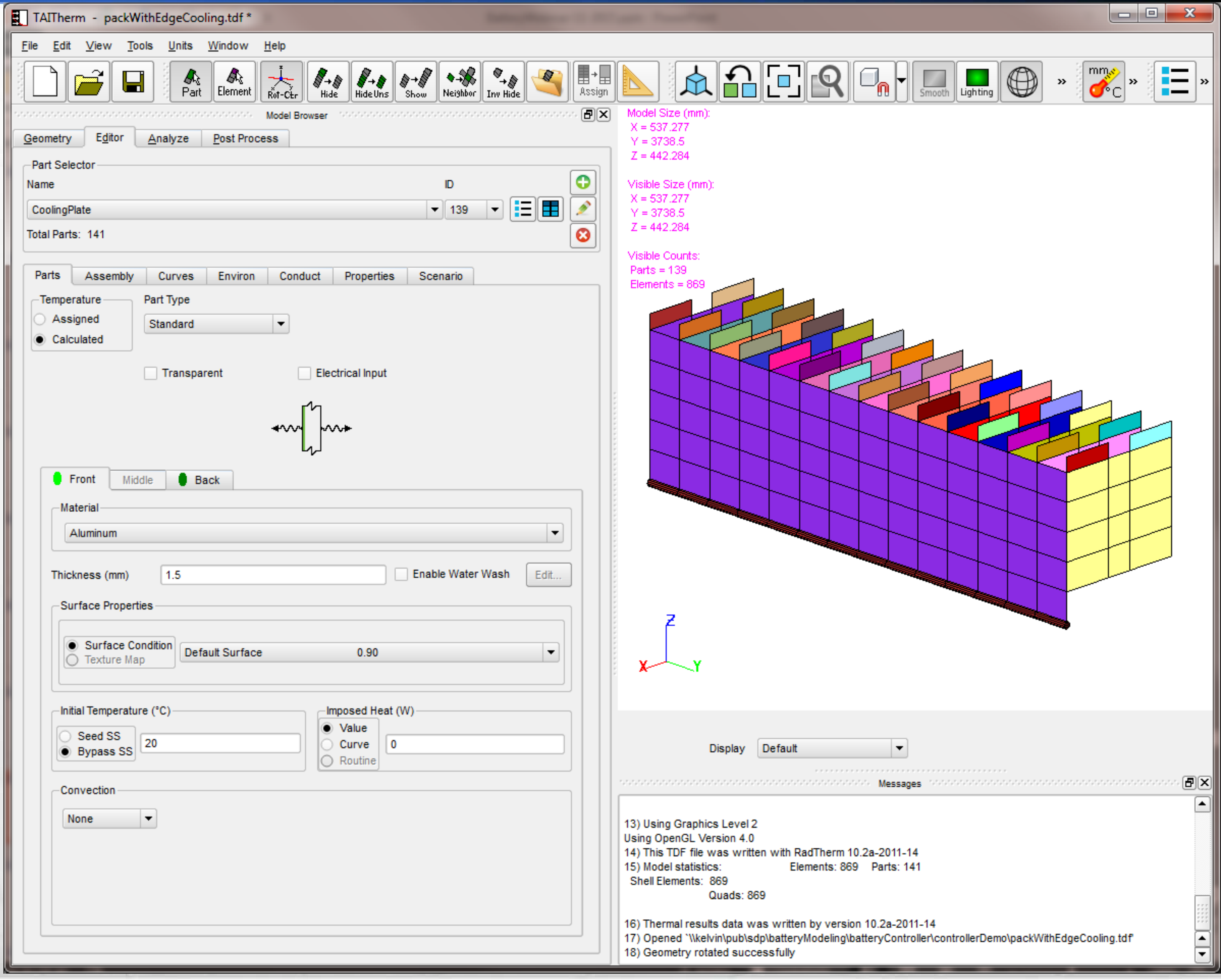
NTG Equivalent Circuit Model – Pack with Different Cooling Concepts

- Edge conduction to liquid-cooled plate



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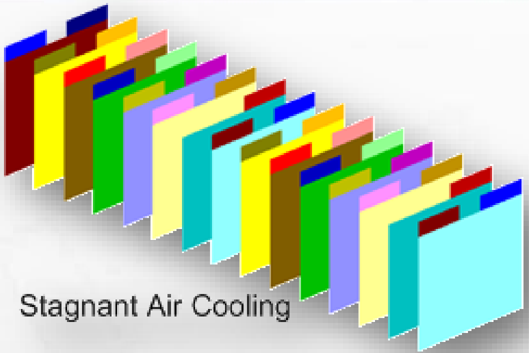
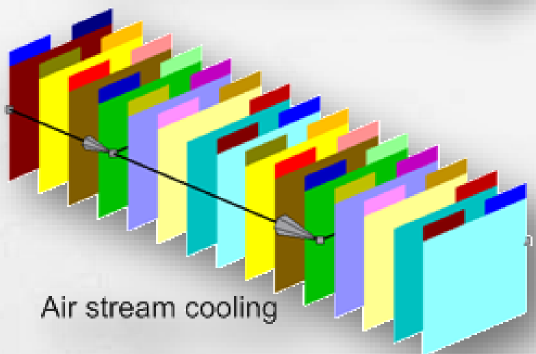
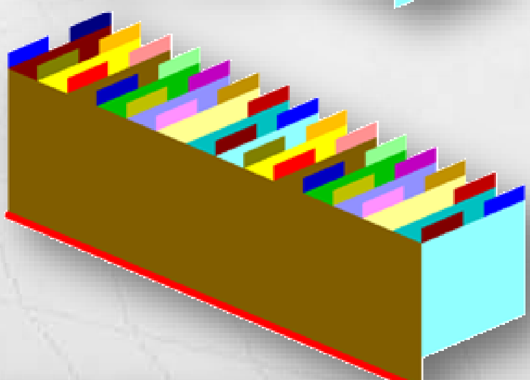
NTG Equivalent Circuit Model – Pack with Different Cooling Concepts



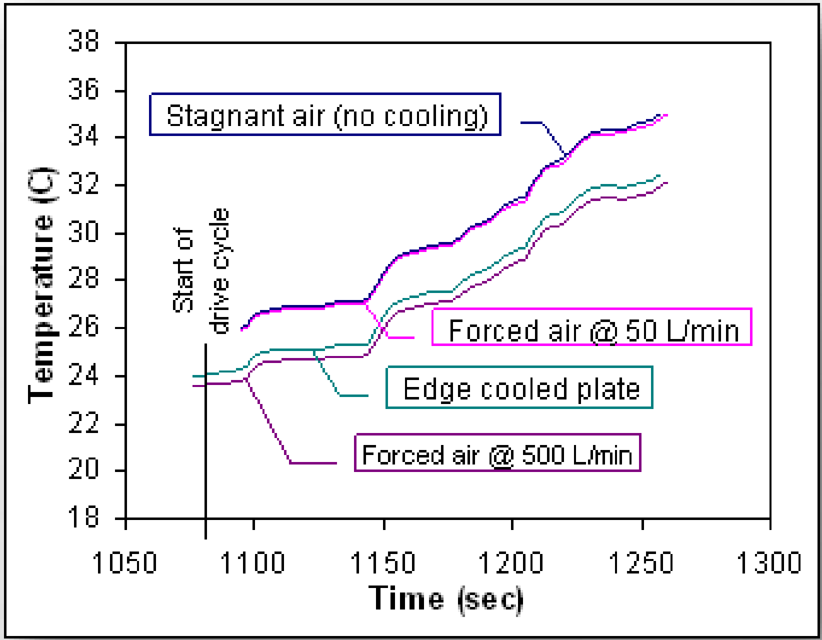
Stagnant Air Cooling



Air stream cooling



Edge cooling to cold plate



- Evaluate effectiveness of cooling strategies
  - Temperature limits
  - Cell-to-cell cooling uniformity
- Determine requirements for cooling system parameters
  - e.g. Flow rates

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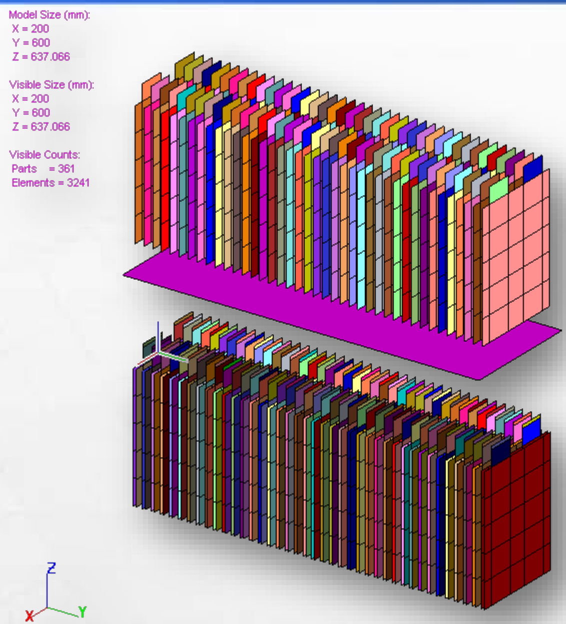
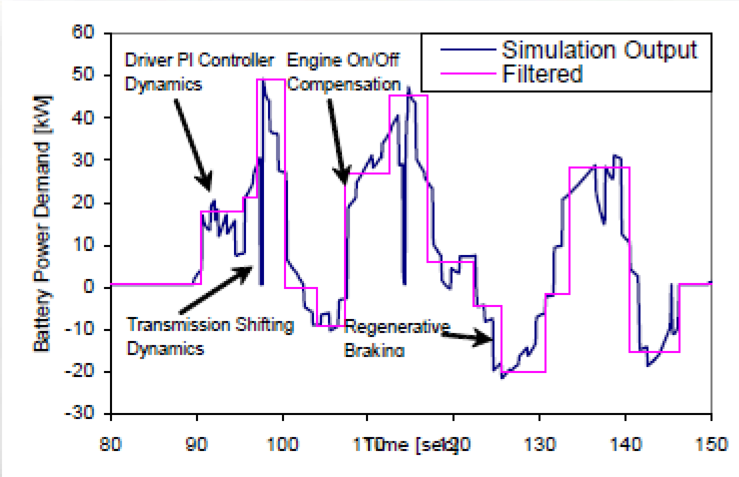
NTG Distributed Model –
Pack During Drive Cycle Analysis





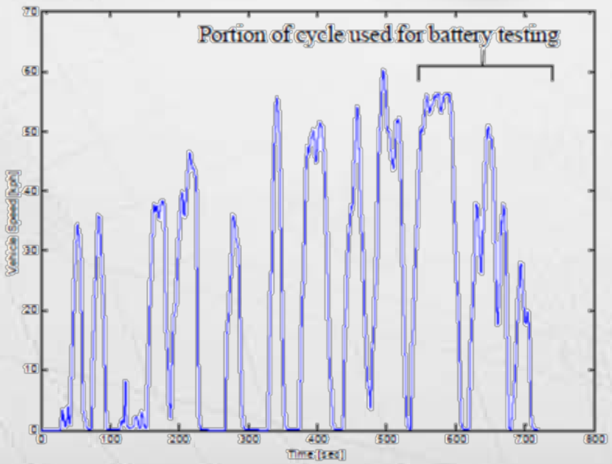
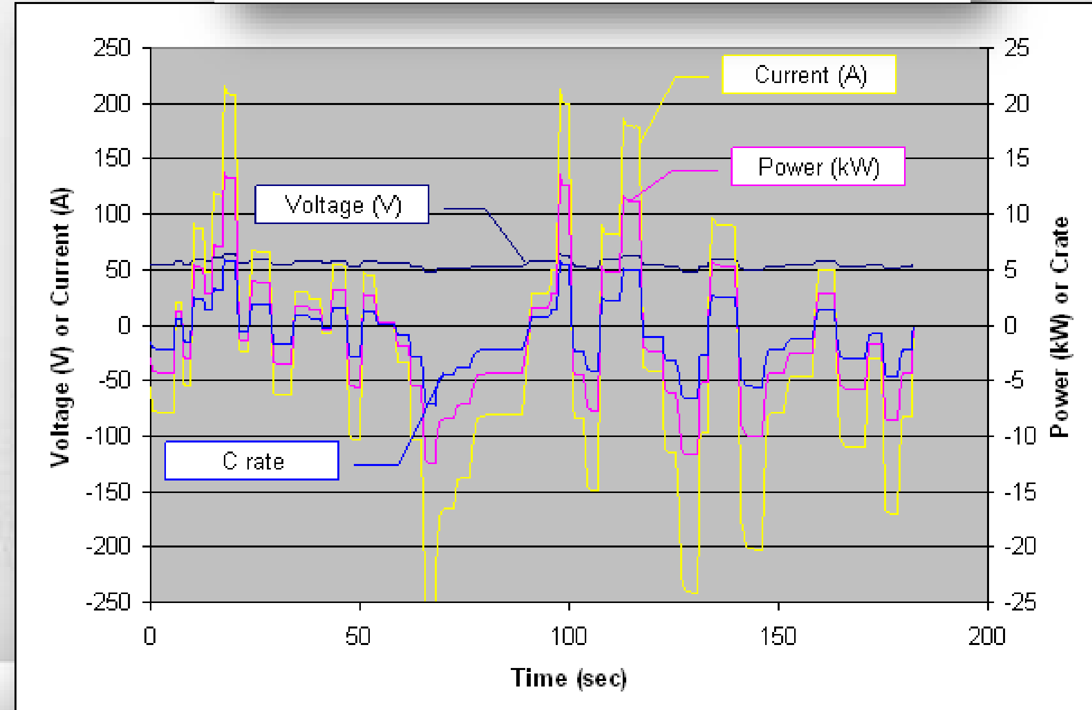
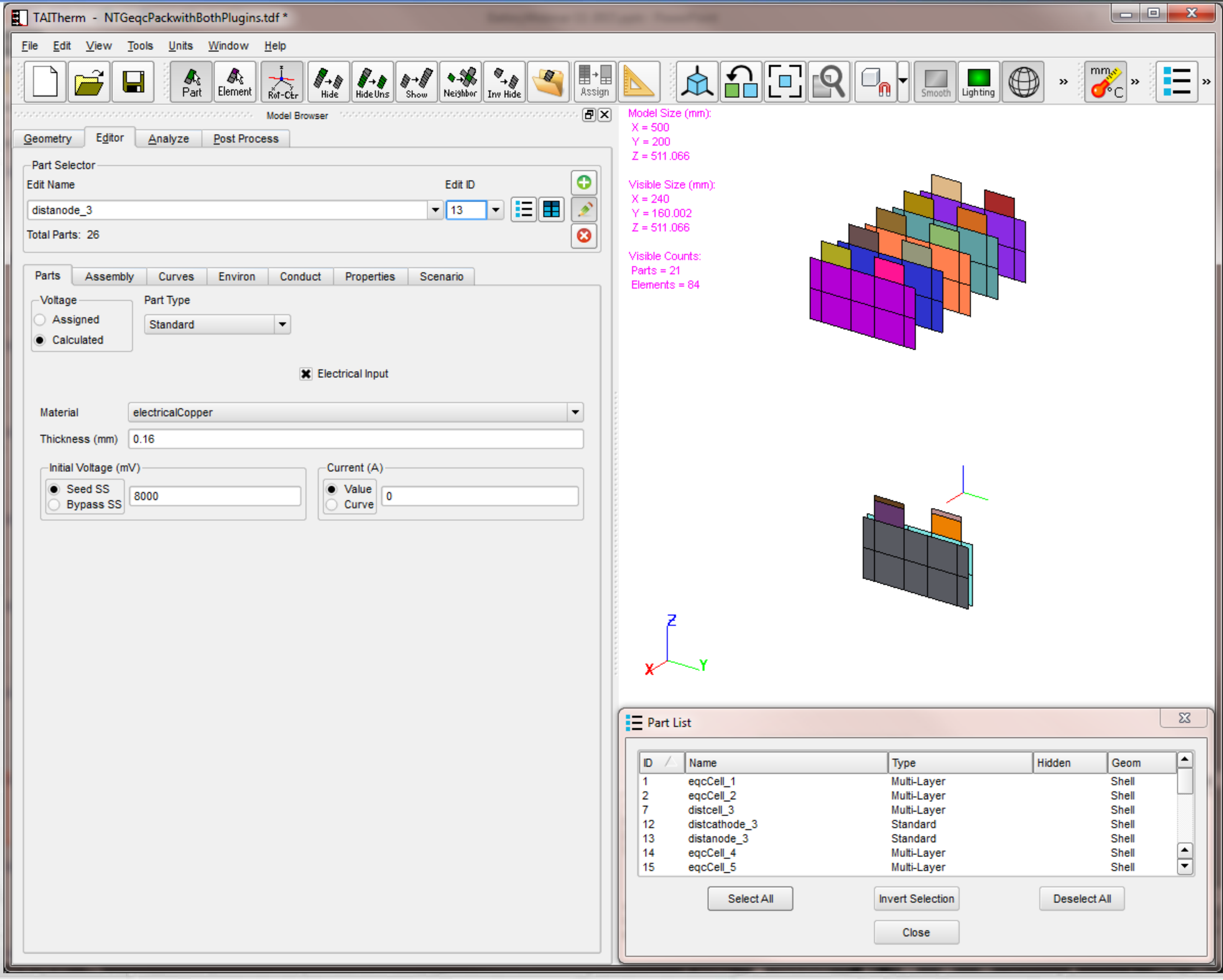


Fig. 2. Full INRETS URB1 Vehicle Test Cycle.



Combined Equivalent Circuit & Distributed Models

- It is possible to combine models
- Investigate detailed electrical and thermal behavior of a cell of interest in a pack without the computational overhead of a full distributed model



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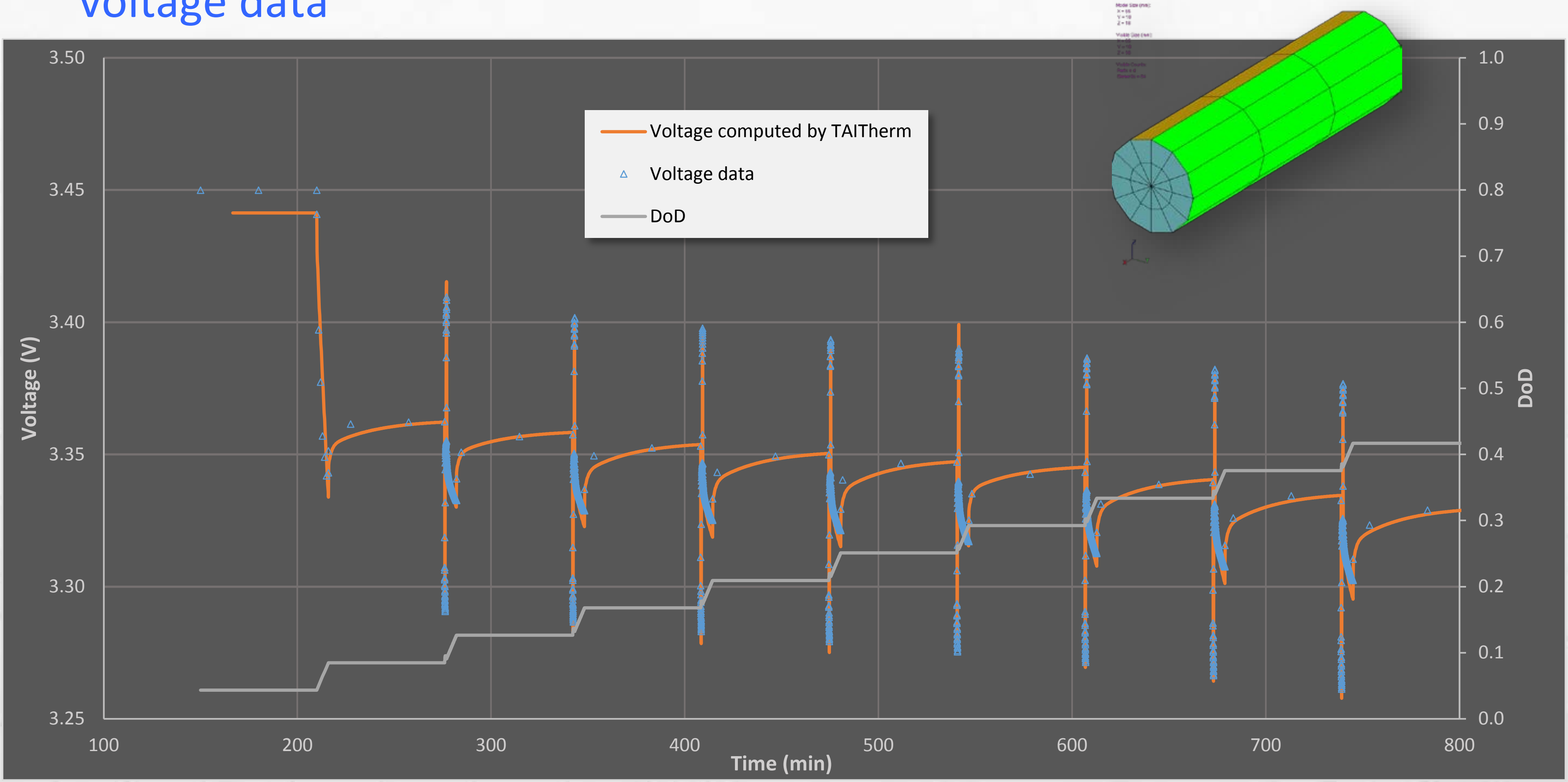
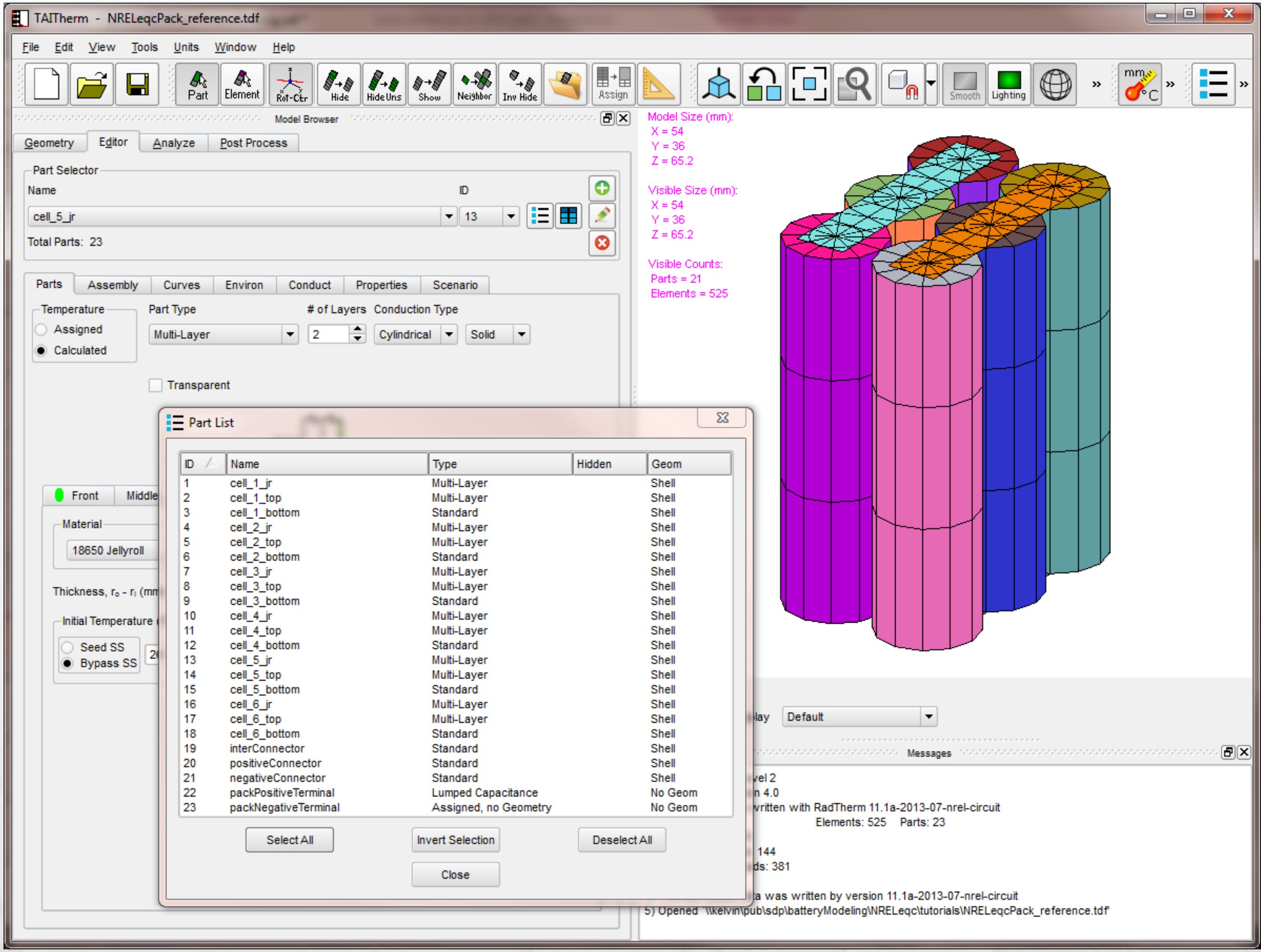
NREL Equivalent Circuit Model of Transient Pulse Data

- Terminal voltage predicted by TAITherm compared to transient voltage data



NREL Equivalent Circuit Model – Pack of Cylindrical Cells

- Radiation between complex geometry is quickly and accurately modeled
  - Can be key component of propagation of thermal runaway



ID	Name	Type	Hidden	Geom
1	cell_1_jr	Multi-Layer		Shell
2	cell_1_top	Multi-Layer		Shell
3	cell_1_bottom	Standard		Shell
4	cell_2_jr	Multi-Layer		Shell
5	cell_2_top	Multi-Layer		Shell
6	cell_2_bottom	Standard		Shell
7	cell_3_jr	Multi-Layer		Shell
8	cell_3_top	Multi-Layer		Shell
9	cell_3_bottom	Standard		Shell
10	cell_4_jr	Multi-Layer		Shell
11	cell_4_top	Multi-Layer		Shell
12	cell_4_bottom	Standard		Shell
13	cell_5_jr	Multi-Layer		Shell
14	cell_5_top	Multi-Layer		Shell
15	cell_5_bottom	Standard		Shell
16	cell_6_jr	Multi-Layer		Shell
17	cell_6_top	Multi-Layer		Shell
18	cell_6_bottom	Standard		Shell
19	interConnector	Standard		Shell
20	positiveConnector	Standard		Shell
21	negativeConnector	Standard		Shell
22	packPositiveTerminal	Lumped Capacitance		No Geom
23	packNegativeTerminal	Assigned, no Geometry		No Geom

Select All · Invert Selection · Deselect All · Close

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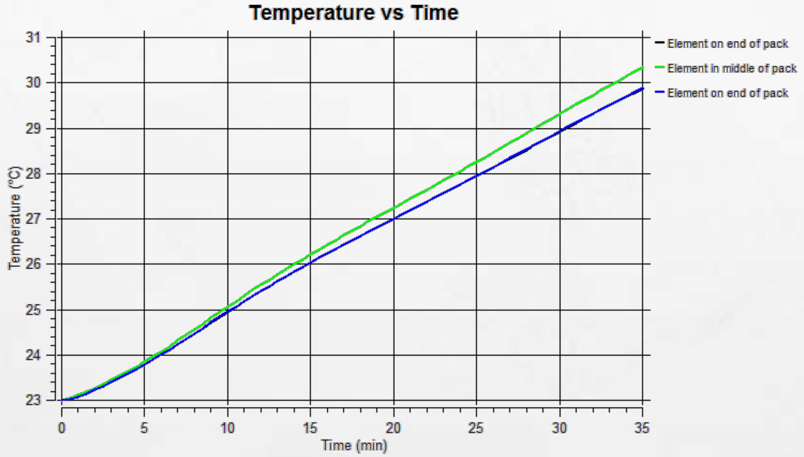
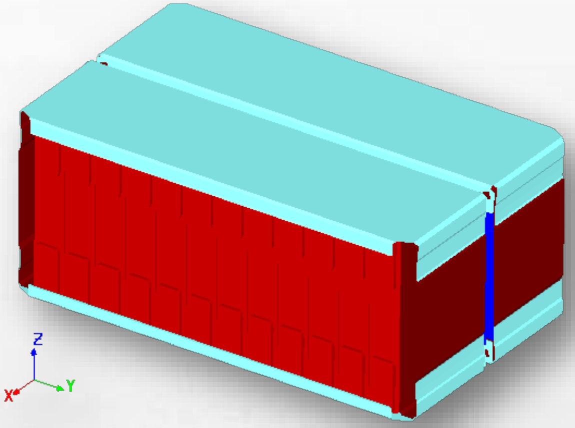
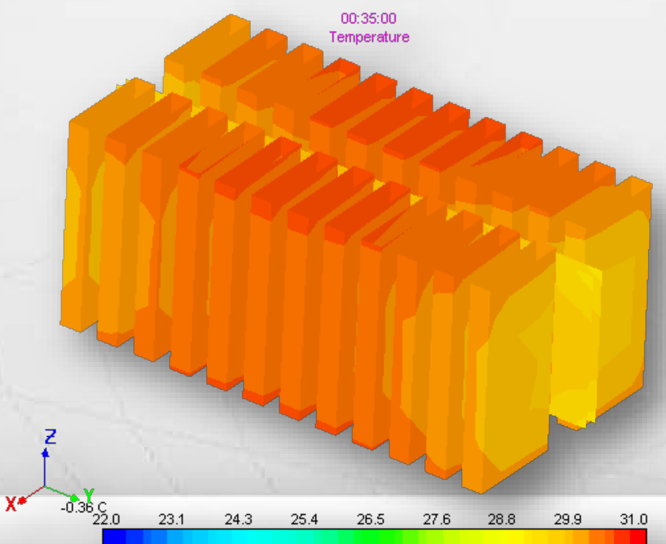
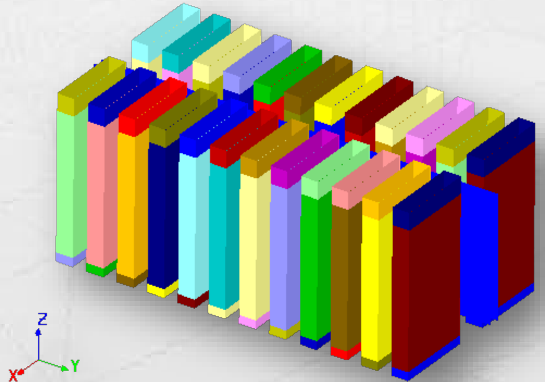
Design Study for OEM

- Single pack (24 cells) and case
- 40 A current









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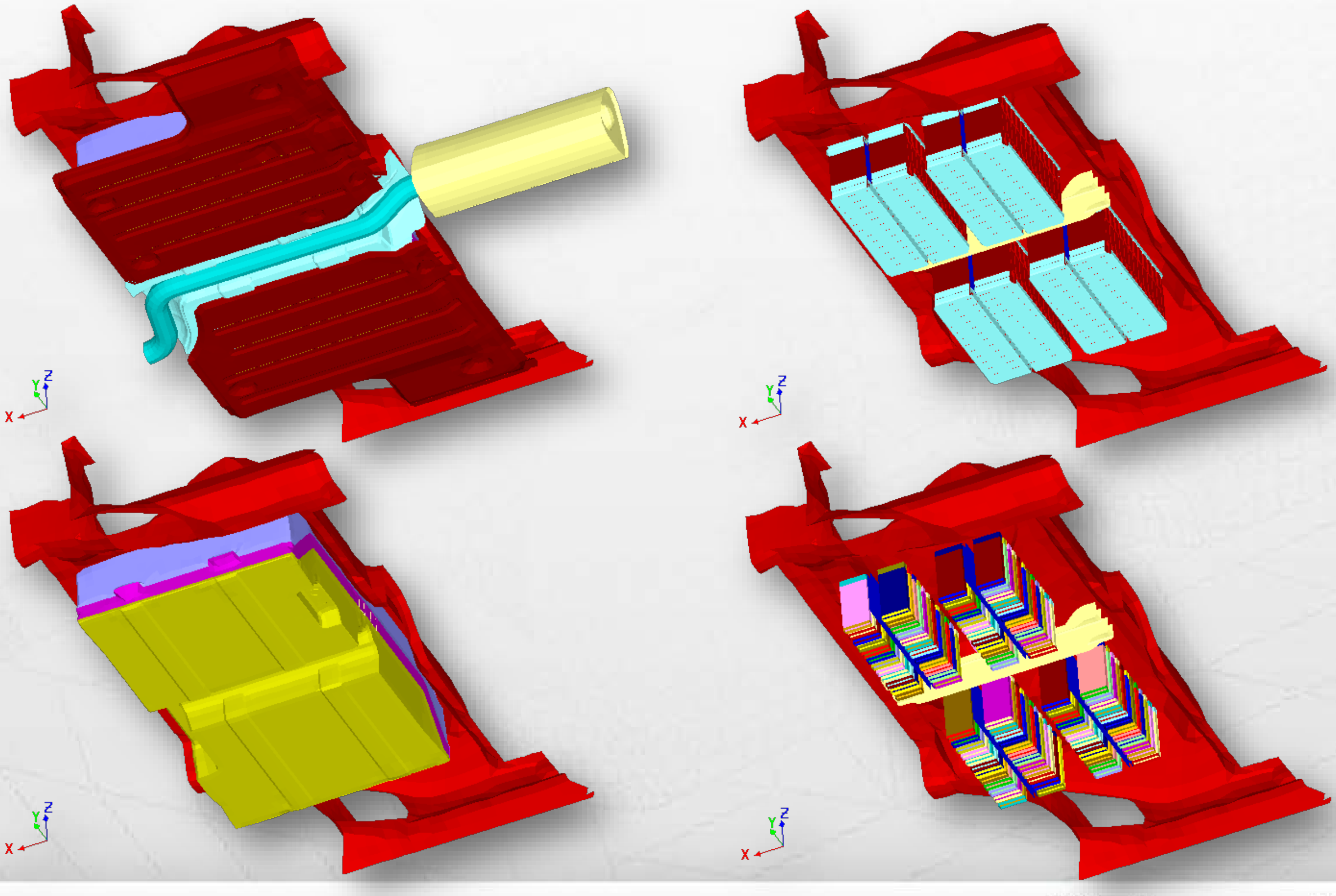
Underbody Analysis – Full Pack with Exhaust

- 96 cells, battery case, exhaust line, insulation
- 25 A current



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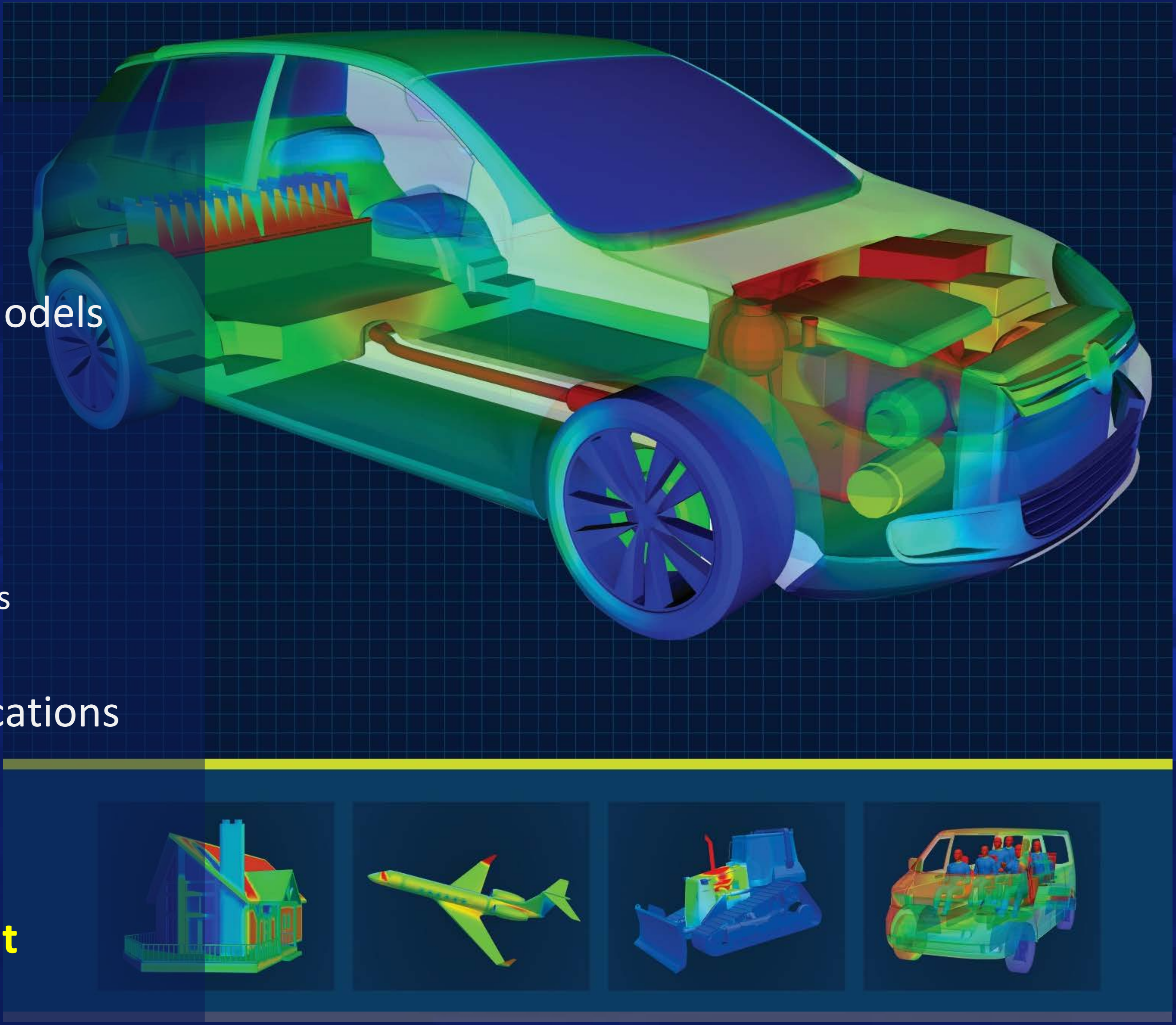
Agenda

- Background
  - Design issues
  - Modeling issues
- TAITherm Battery Models
  - Physical description
  - Modeling concepts
  - Relative strengths
- Input Requirements
  - Electrical parameters
  - Thermal parameters
- Use in Typical Applications
  - Single cells
  - Pack / module
  - System integration
- **Future Development**
  - **Runaway model**
  - **Life model**



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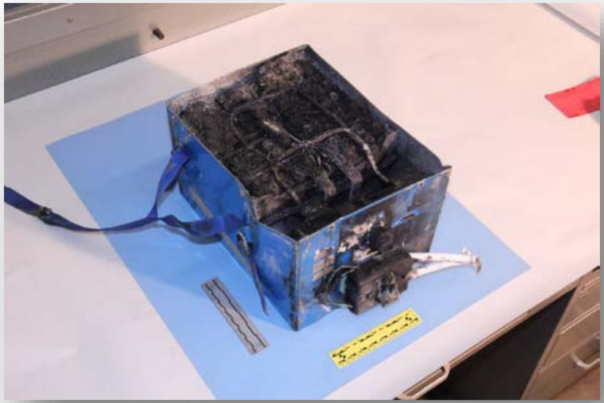
NREL Thermal Runaway Model

- Describes heating from unwanted chemical reactions at elevated temperatures
  - Elevated temperatures due to hot ambient conditions, I^2R heating at shorts, internal discharge
- Temperature-dependent imposed heating derived from reaction kinetics



- Use to evaluate risk of thermal runaway or failure for plausible failure scenarios, evaluate mitigation strategies

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NREL Life Predictive Model

- Describes capacity and resistance changes over time as a function of stress statistics
  - Calendar fade: function of T(t), SOC(t)
  - Cycling fade: function of DSOC, T, C_{rate}, DT
- TAITherm runs generate life operating statistics, which are then input to life predictive model

- Use to estimate time to end-of-life, performance characteristics at end-of-life

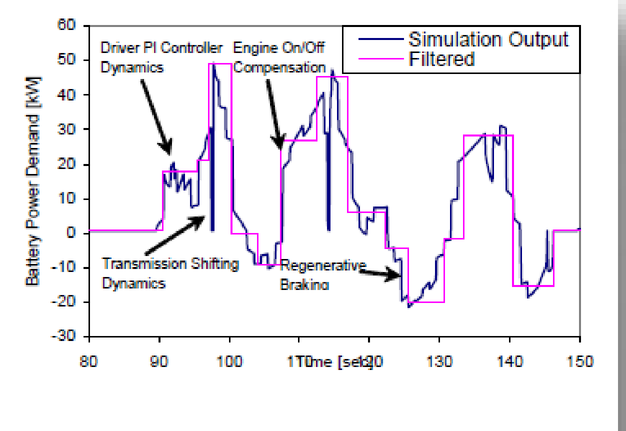
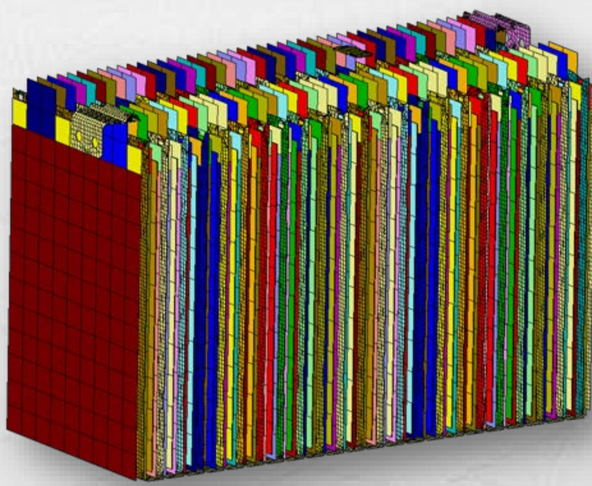


Fig. 4. Enlargement of Filtered and Unfiltered Battery Test Cycle.



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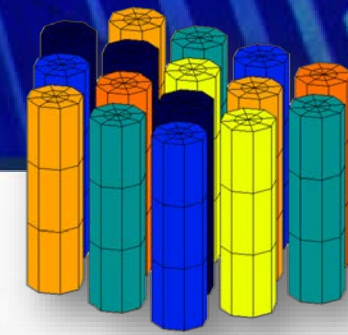
Summary



- TAITherm can be used to address battery thermal design issues
  - Cell, pack, and system integration

- 3 battery models in TAITherm provide flexible tools for optimized design / analysis process
  - Efficient transient modeling
  - Representative thermal environment

- Validation info:
  - Peck, S., Pierce, M., “Development of a Temperature-Dependent Li-ion Battery Thermal Model”, SAE 2012-01-0117
  - Peck, S., Olszanski, T., Zanardelli, S., Pierce, M., “Validation of a Thermal-Electric Li-Ion Battery Model”, SAE 2012-01-0332
  - Peck, S., Velivelli, A., Jansen, W., “Options for Coupled Thermal-Electric Modeling of Battery Cells and Packs”, SAE 2014-01-1834

Questions

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