NREL
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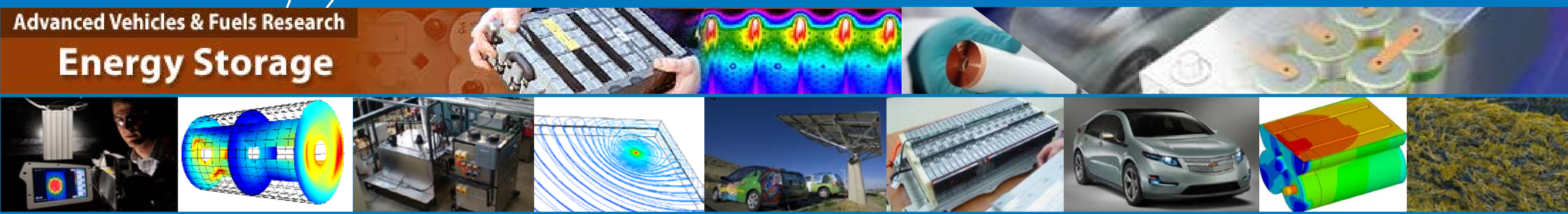
Tools for Designing Thermal Management of Batteries in Electric Drive Vehicles



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Golden, Colorado

Presented at the
Large Lithium Ion Battery Technology & Application Symposia
Advanced Automotive Battery Conference
Pasadena, CA • February 4-8, 2013

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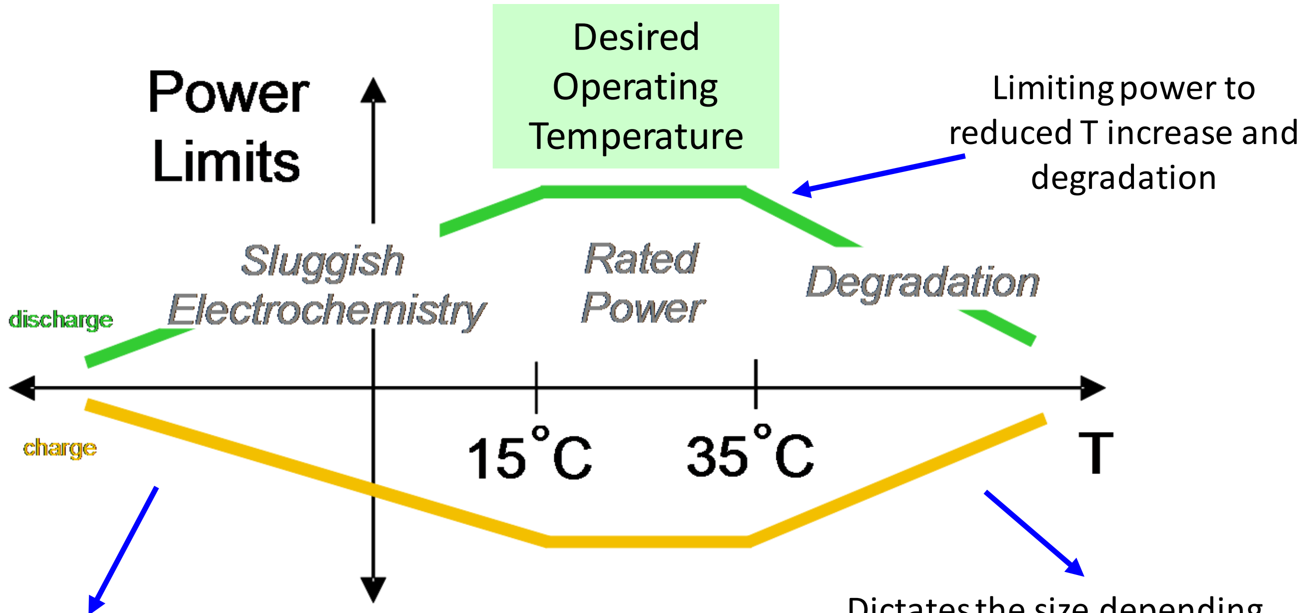
Battery Temperature in xEVs

- Lithium-ion battery (LIB) technology is expected to be the energy storage of choice for electric drive vehicles (xEVs) in the coming years
- Temperature has a significant impact on life, performance, safety, and cost of LIBs



Dictates power capability through cold cranking

Dictates the size depending on the power and energy fade rate

Also limits the electric driving range

Kandler Smith, NREL Milestone Report, 2008

Battery Thermal Management for xEVs

- **Higher temperatures degrade LIBs more quickly, while low temperatures reduce power and energy capabilities, resulting in cost, reliability, safety, range, or drivability implications**
- **Therefore, battery thermal management is needed for xEVs to:**
  - Keep the cells in the desired temperature range
  - Minimize cell-to-cell temperature variations
  - Prevent the battery from going above or below acceptable limits
  - Maximize useful energy from cells and pack
  - Use little energy for operation
- **However, a battery thermal management systems (BTMS) could:**
  - Increase complexity
  - Add cost
  - Reduce reliability
  - Consume energy for operation
  - …

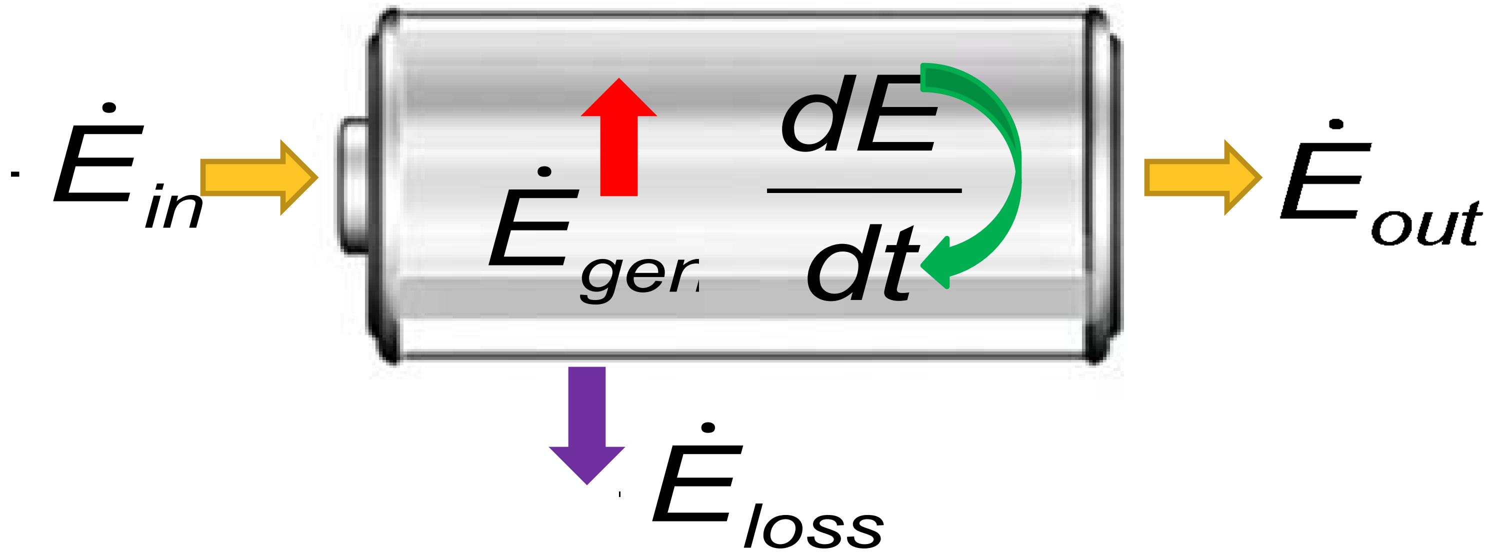
Battery Thermal Management System

- Most in the xEV battery community agree that the value that a BTMS provides in increasing battery life and improving performance outweighs its additional cost and complexity
- However, the BTMS needs to be designed appropriately with the right tools
- The National Renewable Energy Laboratory has been a leader in battery thermal analysis and characterization for aiding industry to design improved BTMSs
- This presentation describes the tools that NREL has used and that we believe are needed to design properly sized BTMSs

Energy Balance in a Battery

$$\frac{dE}{dt} = \dot{E}_{gen} - \dot{E}_{loss} + \dot{E}_{in} - \dot{E}_{out}$$

Energy Accumulation Rate	Energy Generation Rate	Energy Loss Rate	Input Energy Rate	Output Energy Rate

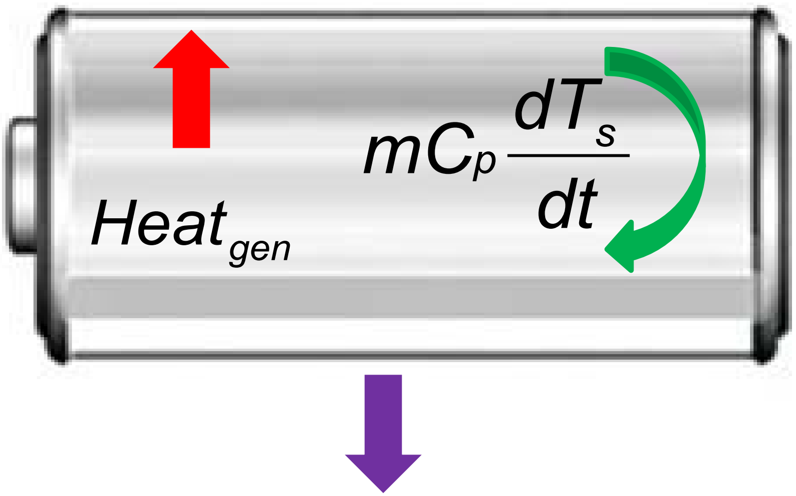


Heat Transfer in a Battery

(Assumption: isothermal ~ very high thermal conductivity)

$$mC_p \frac{dT_s}{dt} = Heat_{gen} - hA(T_s - T_a) - e\delta A(T_s^4 - T_a^4) - Q_{Ext\_conduction}$$

Rate of Temp Change	Rate of Internal Heat Generation	Convection Heat Rate	Radiation Heat Rate	Conduction Heat Rate



$$hA(T_s - T_a) + e\delta A(T_s^4 - T_a^4) + Q_{Ext\_conduction}$$

Method of heat rejection/addition for thermal control

Heat generated ($Heat_{gen}$) in a battery consists of:

- Electrochemical reactions
- Phase changes
- Mixing effects
- Joule heating

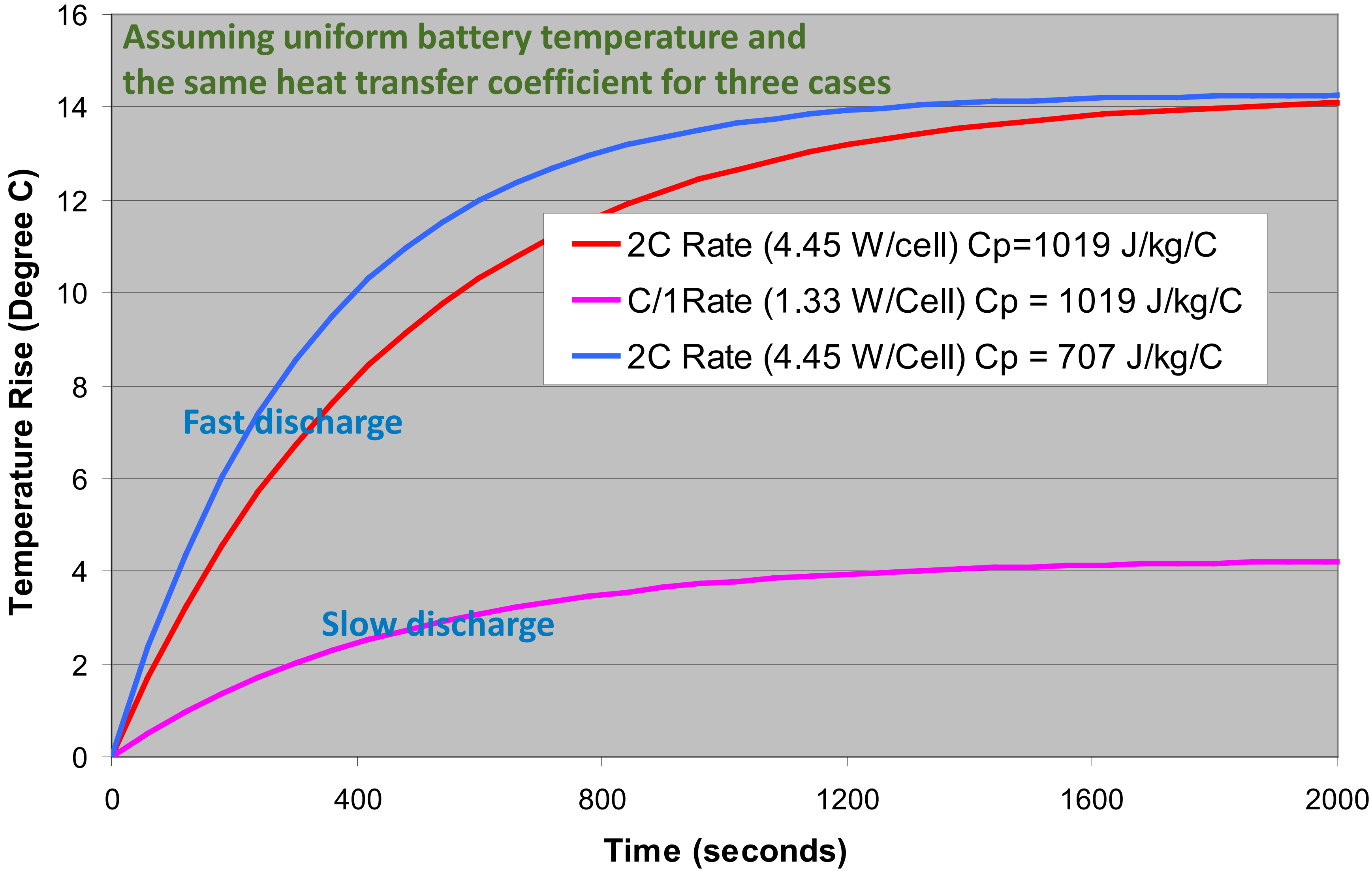
D. Bernardi, E. Pawlikowski and J. Newman

J. Electrochem. Soc. 1985. Volume 132. Issue 1.

T_s = Battery Temp

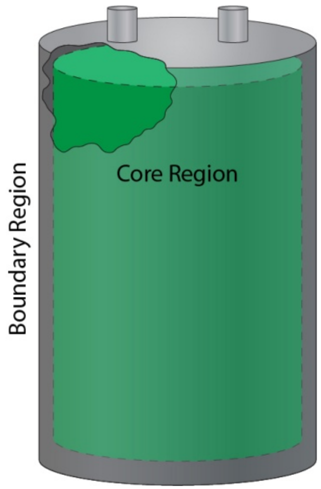
T_a = Ambient Temp

Heat Generation Rate and Specific Heat Impact Battery Temperature Rise



Heat Transfer in a Battery

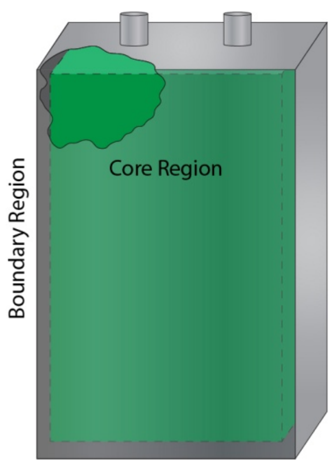
(Non-isothermal; case and core regions)



Core region

$$\rho C_p \frac{\partial T}{\partial t} = Heat_{gen} + \nabla \cdot k \nabla T$$

$k : thermal\ conductivity$



Case or boundary region

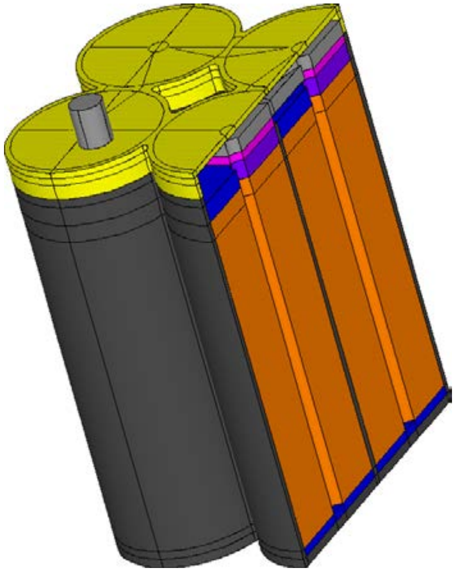
$$-k_{\mathrm{n}} \left. \frac{\partial \mathrm{T}(n)}{\partial n} \right|_{n=0.L} = h(T_{\mathrm{s}} - T_{\infty}) + e\delta(T_{\mathrm{s}}^4 - T_{\infty}^4) + \rho_{\mathrm{B}} C_{\mathrm{p,B}} H_{\mathrm{B}} \frac{\partial T_{\mathrm{B}}}{\partial t}$$

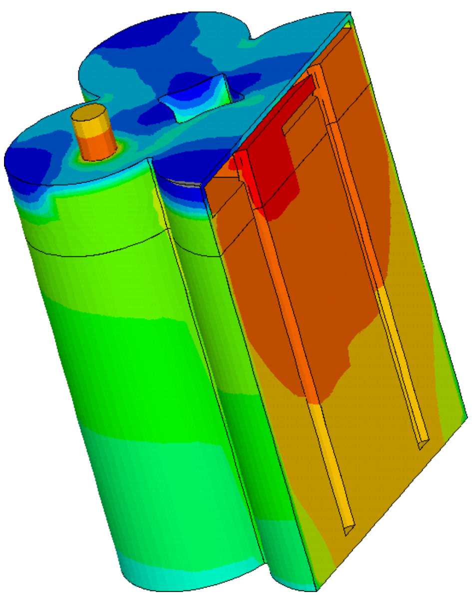
Heat flux from the core	Convection from various case surfaces	Radiation from various case surfaces	Heat accumulation in the case

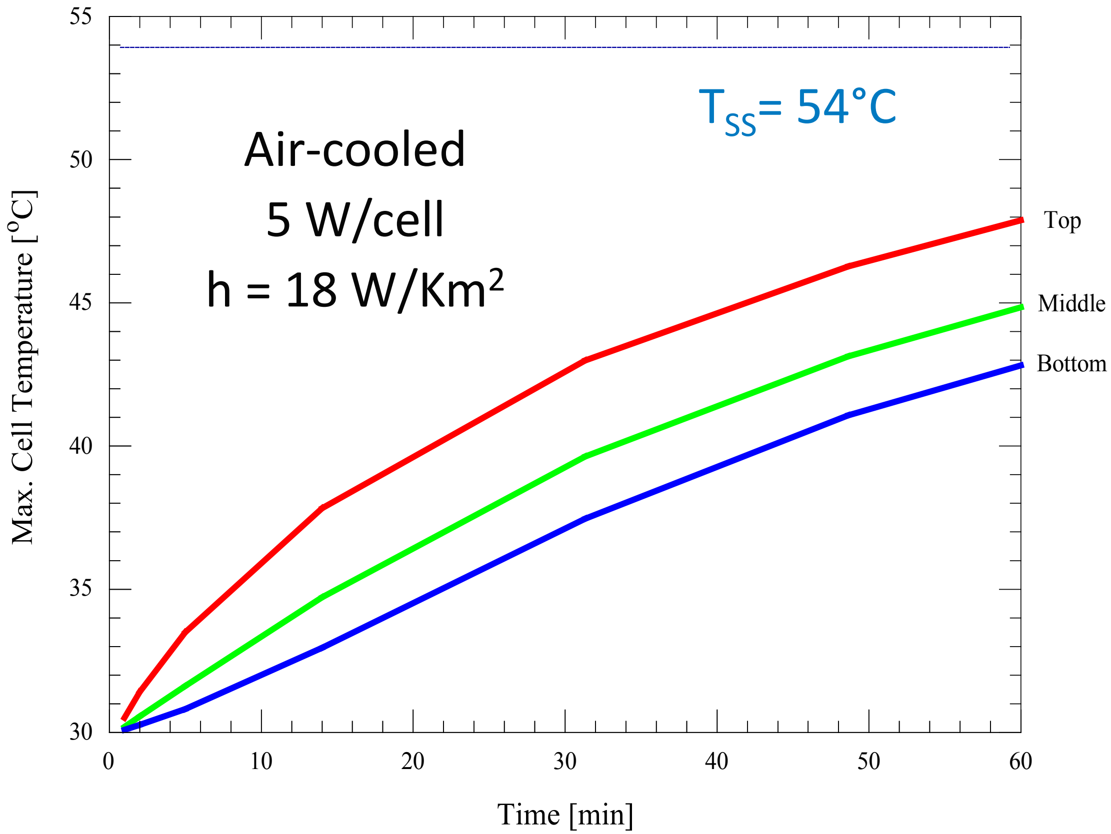
Johnsee Lee, K. W. Choi, N. P. Yao and C. C. Christianson

J. Electrochem. Soc. 1986, Volume 133, Issue 7, Pages 1286-1291

Case + Core Example: T Distribution in a Module







A. Pesaran, A. Vlahinos, S. Burch. Proceedings of the 14th Electric Vehicle Symposium, December 1997

What Information is Needed to Design a BTMS?

- ***Acceptable temperature range*** ***for cell components at all times, i.e., active material, binders, separators, electrolyte, etc.***
- ***Acceptable temperature difference*** ***within cells and from cell to cell, depending on the chemistry and management system***
- ***Maximum and minimum temperature limits*** ***for life specifications, performance ratings, and safety considerations***
- **Thermo-physical properties** **of cells or components (density, specific heat, directional thermal conductivities)**
- **Heat generation rate** **under average and aggressive drive profiles and loads for the specific electric drive**
- **Heat rejection rate** **depending on thermal management strategy**
  - Fluid heat transfer coefficients or sink conductance
  - Cooling fluid flow rate and sink temperature
- **Configurations and dimensions** **of cells and proposed BTMS**
- **Parasitic power** **needed to push fluids/cooling through BTMS**

Tools for Designing BTMS

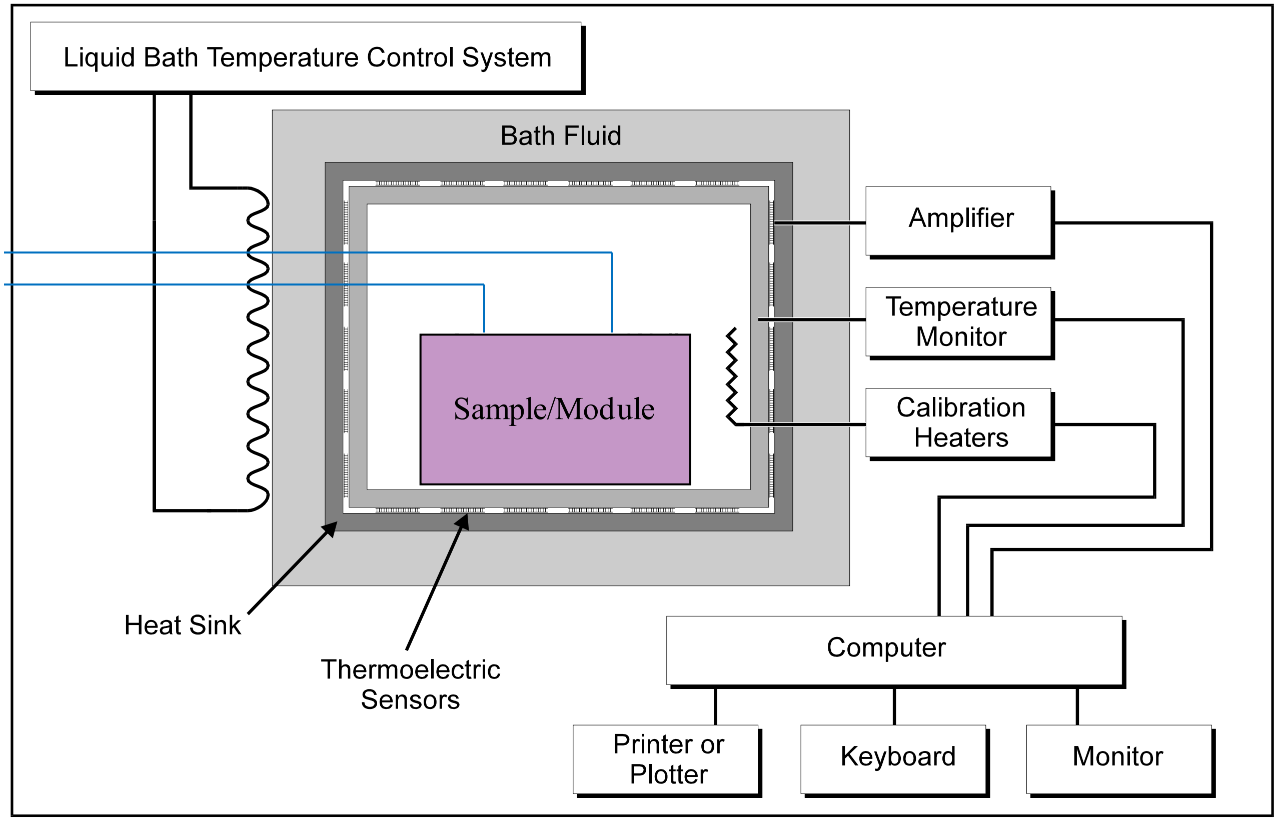
- **Experimental Tools**
  - Isothermal calorimeters and battery testers
  - Infrared thermal imaging
  - Thermal conductivity meters
  - Heat transfer characterization setup
  - Battery thermal testing loop

- **Modeling Tools**
  - First-order/lumped capacitance thermal and fluid models
  - 1-D and 2-D thermal and fluid-flow performance models
  - 1-D vehicle integrated thermal-flow models
  - 3-D electro-thermal models
  - 3-D electrochemical-thermal model
  - Computer-aided engineering software

Isothermal Battery Calorimeters

- We use a single-ended (one test chamber) conduction calorimeter to measure **specific heat** and **heat generation** at various current rates, temperatures, and states of charge (SOCs)

Battery Tester



Initially fabricated by Calorimetry Sciences Corporation; later **improved** by NREL.

A. Pesaran, M. Keyser, D. Russell, J. Crawford, E. Lewis. Presented at the Long Beach Battery Conference, January 1998

NREL's First Isothermal Battery Calorimeter

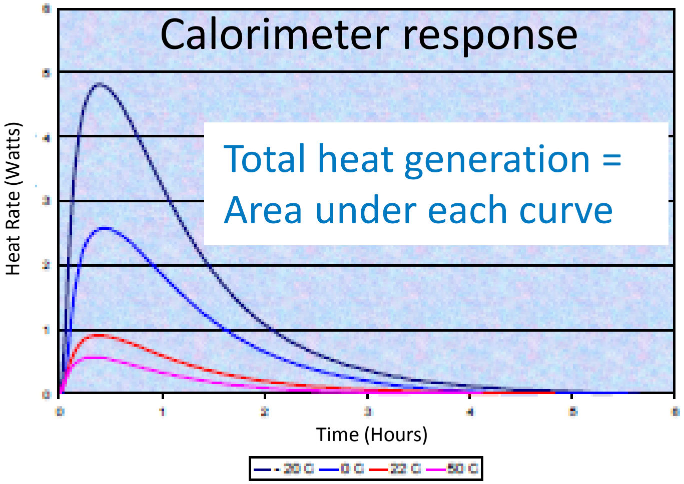
- Heat flux measured between the sample and a heat sink using heat flux gauges
- The heat sink is kept at a constant temperature with a precise isothermal bath

- Max module that could be tested: 21 cm x 20 cm x 32 cm
- Heat rate detection: 0.015 W to 100 W
- Minimum detectable heat effect: 15 J (at 25°C)
- Baseline stability: ±10 mW
- Temperature range: -30°C to 60°C (±0.001°C)
- Accuracy of better than ±3%

Calorimeter

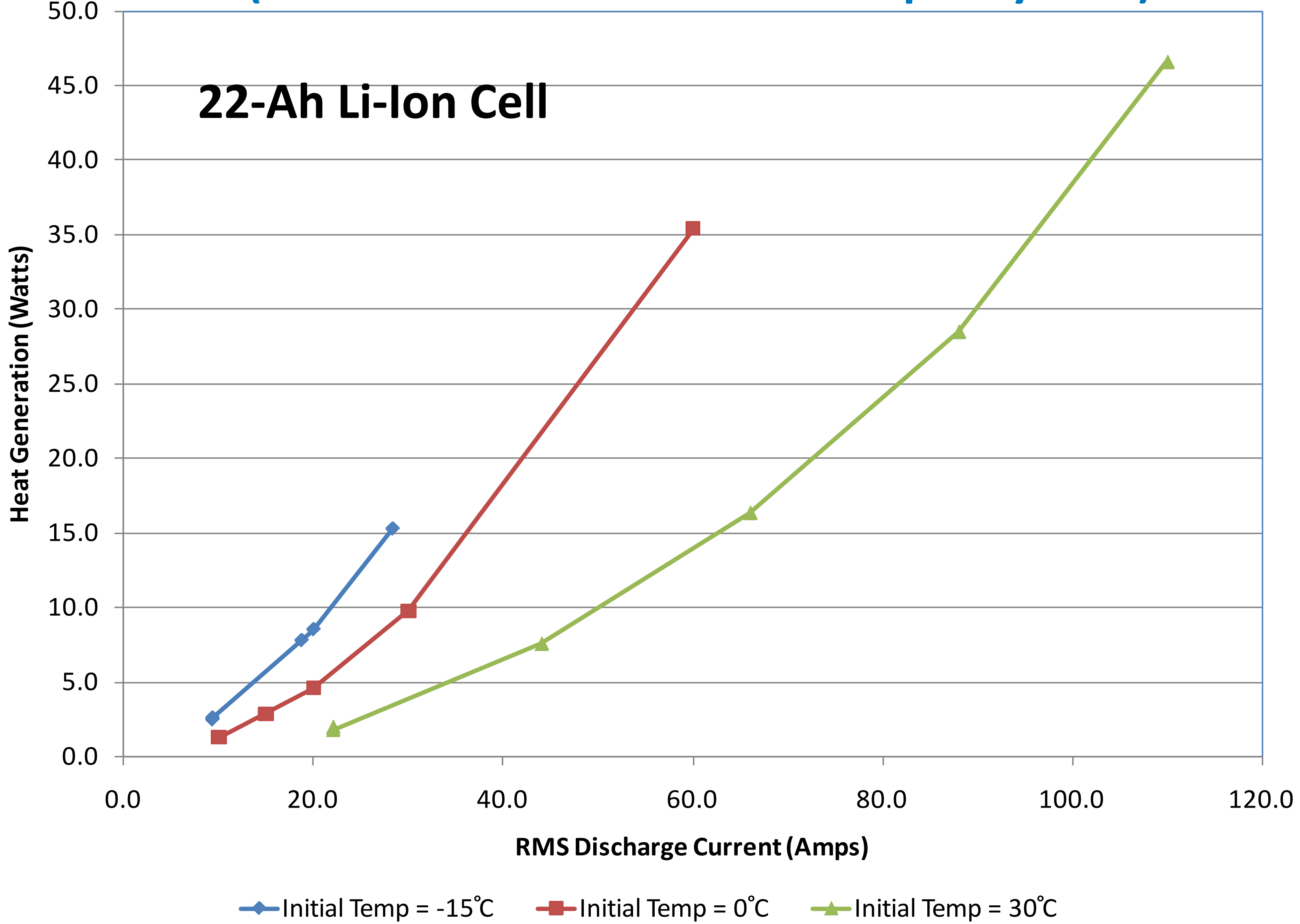
Calorimeter Cavity

Photo Credits: David Parson & Matt Keyser, NREL



Example Heat Generation Data for CC Discharge

(from max to min allowable capacity-SOC)



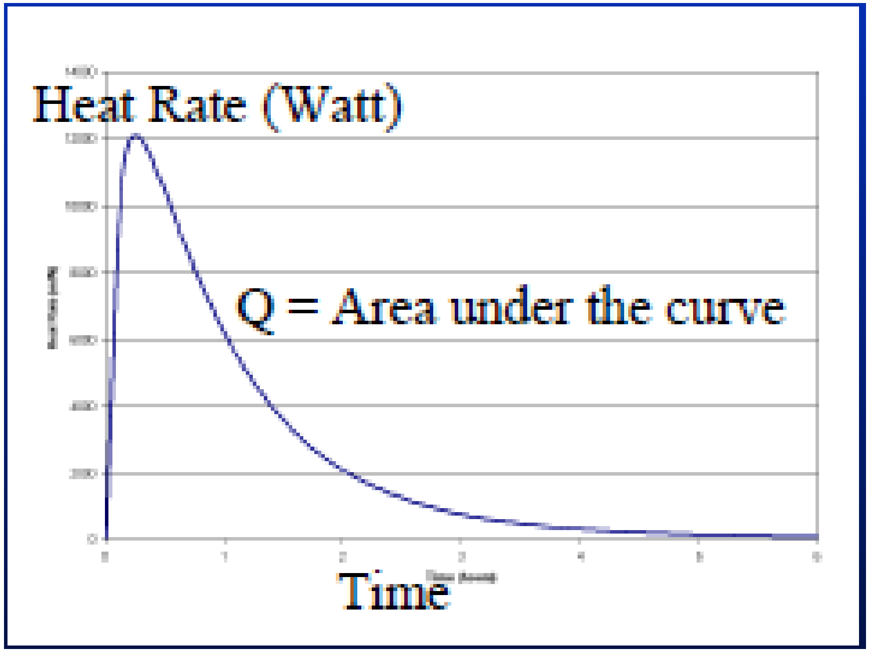
Specific Heat (Heat Capacity)

- **Can be estimated from constituents of cell/module**

$$C_{p,ave} = \sum_{1}^{n} (C_{p,i} \bullet m_i) / \sum_{1}^{n} m_i$$

- **Can be estimated using a calorimeter by measuring heat lost/gained (Q) from the battery going from $T_{initial}$ to T_{final}**
  - Heat capacity is calculated by

$$C_{p,ave} = Q / (m_{total} \bullet (T_{initial} - T_{final}))$$



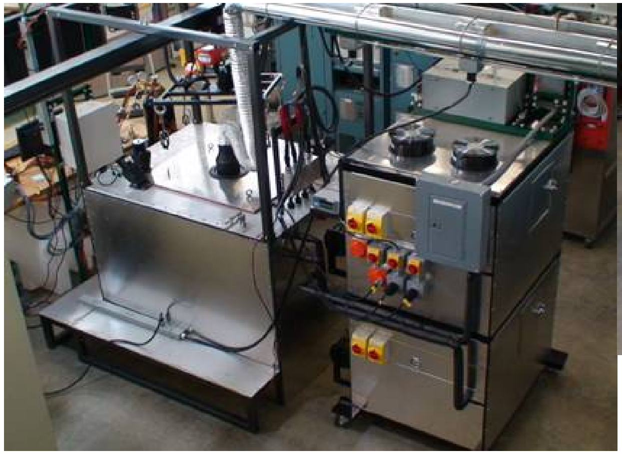
Cell/Module	$T_{average}$ (°C)	Heat Capacity J/kg/°C
NiMH – 18 Ah	33.2	677
Li-Ion 18650	33.1	1,105
Li-Ion Pouch – 4 Ah	18	1,012
VRLA – 16.5 Ah	32	660
Ni Zn – 22 Ah	20	1,167

Thermal Characteristics of Selected EV and HEV Batteries, A. Pesaran, M. Keyser. Presented at the 16th Annual Battery Conference; Long Beach California, January 2001

NREL's Large Volume Battery Calorimeter

- **Single chamber, conduction, isothermal**
- **Includes several patent-pending concepts**
- **Test chamber submerged**
- **Capability to test liquid-cooled batteries**
- **Safety features in case of events**
- **Test chamber 6 times larger than the NREL module calorimeter**
    - 2 ft x 2 ft x 4 ft
- **Heat Rate: 0.05 W to 4 kW**
- **Accuracy of heat meas. ±3%**

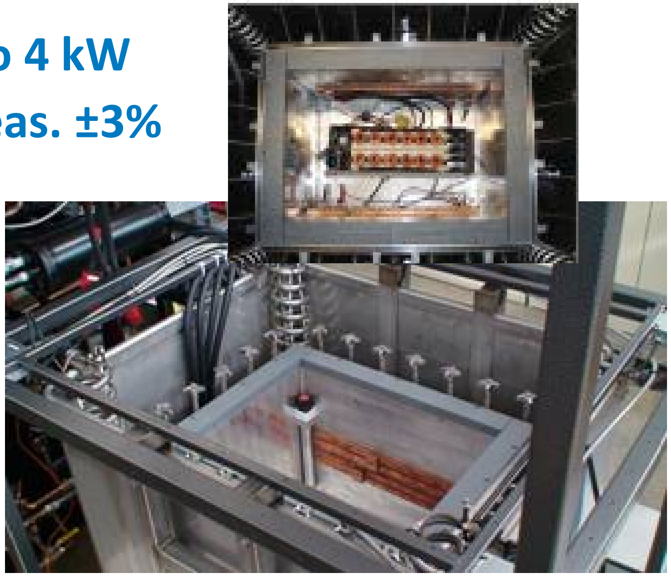
Photo Credits: Dennis Schroder & Ahmad Pesaran, NREL



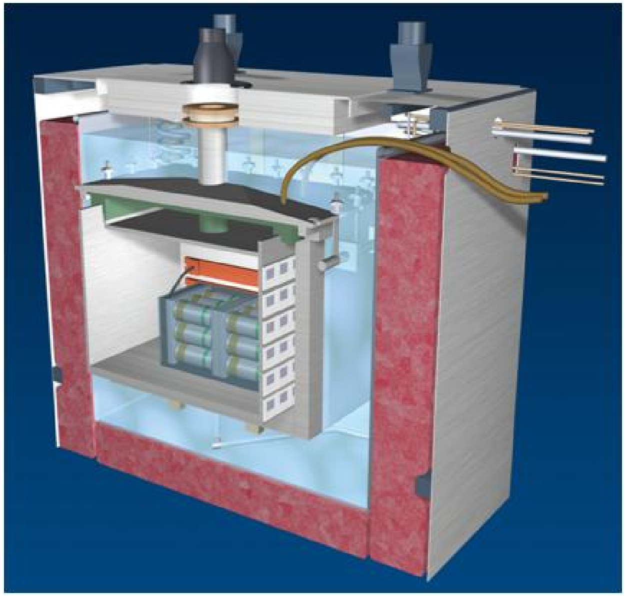
Completed System with Heating/Cooling Unit

Test Chamber

Flux Gauges in Test Chamber



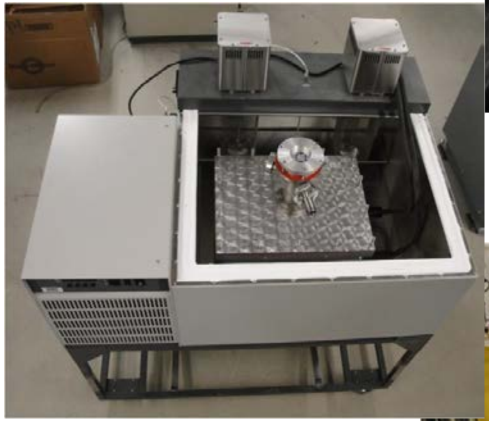
Test Chamber in Isothermal Bath



NREL's New Isothermal Cell Calorimeter

- Single chamber, conduction, isothermal
- Test chamber submerged under isothermal bath
- Testing chamber: 15 cm W x 10 cm L x 6 cm H
- Heat detection limit: 1 mW and 10 J
- Initial testing shows excellent baseline stability and an error of less than ±1.6%
- CRADA and license agreement signed with NETZSCH to commercialize NREL's battery calorimeter design

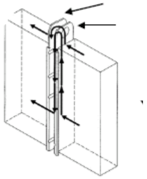
Photo Credits: Dennis Schroder & Dirk Long, NREL

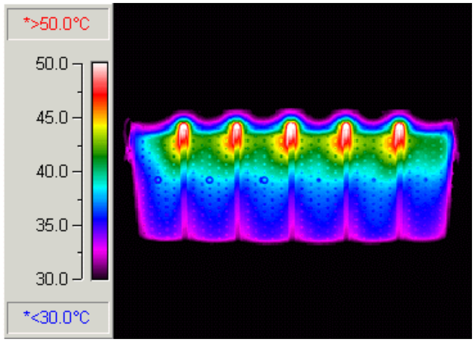


http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/50558.pdf

Infrared Thermal Imaging

- **Quickly finds thermal signature of the whole cell under electrical loads**
- **Helps understand thermal behavior, creates diagnostics, and improves designs**
- **Could be used as a validation of thermal models**
- **Thermal signature depends on several factors**
  - Geometry, thermal conductivity of case and core, location of terminals, design of interconnects, current density, current profile, chemistry, environment
- ***We spray a thin layer of boron nitride on all the surfaces of the face that needs to be imaged***
- ***We minimize reflections from other objects by placing the cells in a non-reflective environment***
- ***We usually test three cells to see the impact of power cable connected to the two end cells***





Thermal image of a 6.5-Ah NiMH module from a MY 2002 Prius under 100A CC discharge

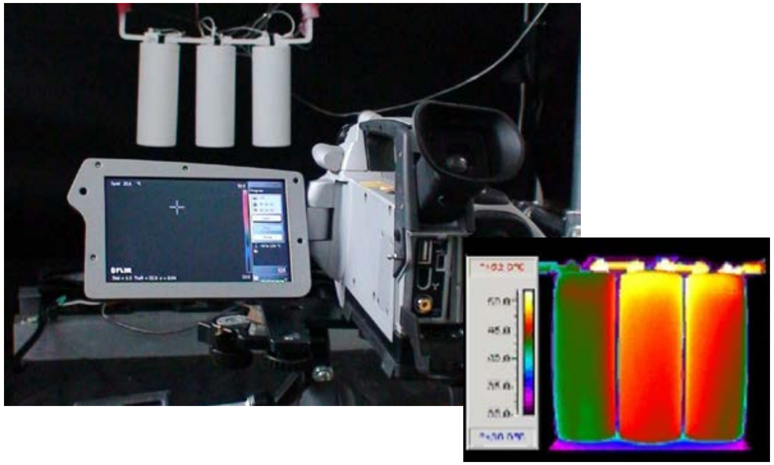
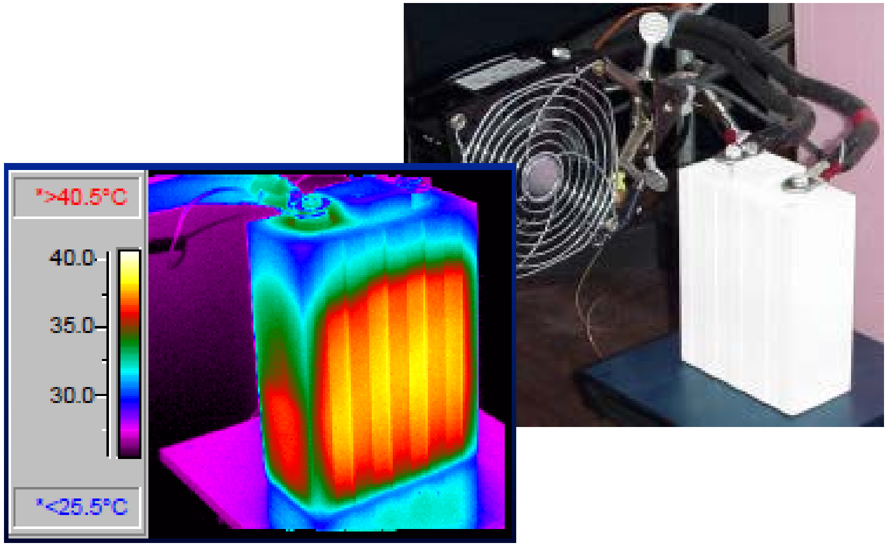
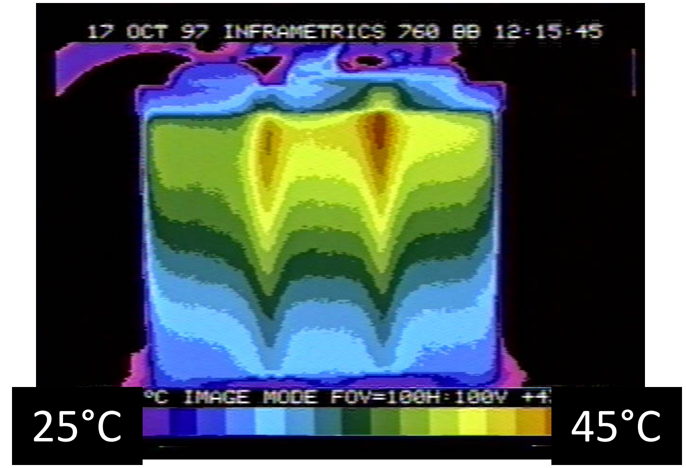
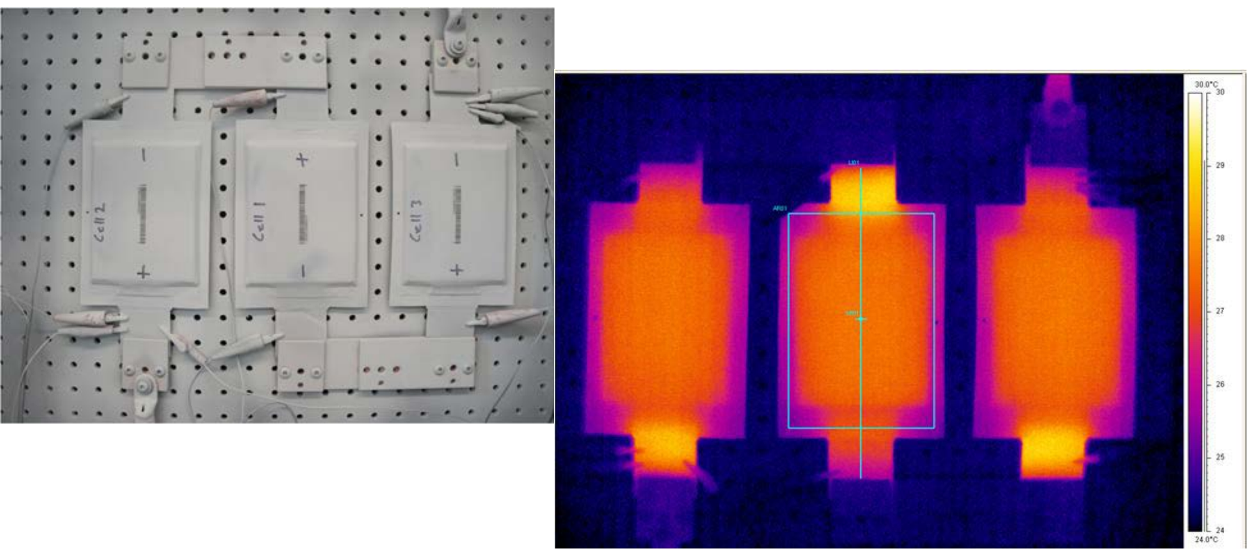


Photo Credits: Matt Keyser, NREL

Examples of Battery Infrared Thermal Imaging







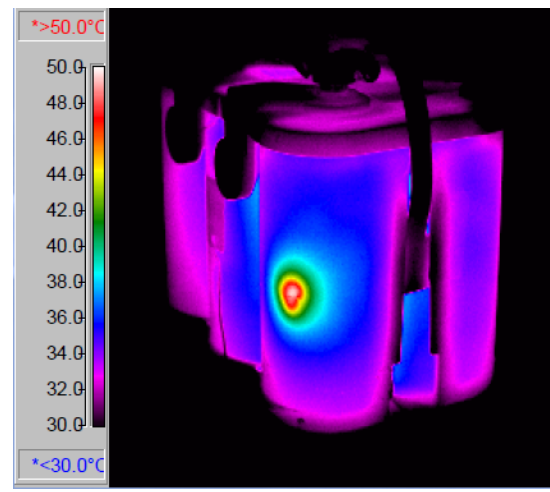
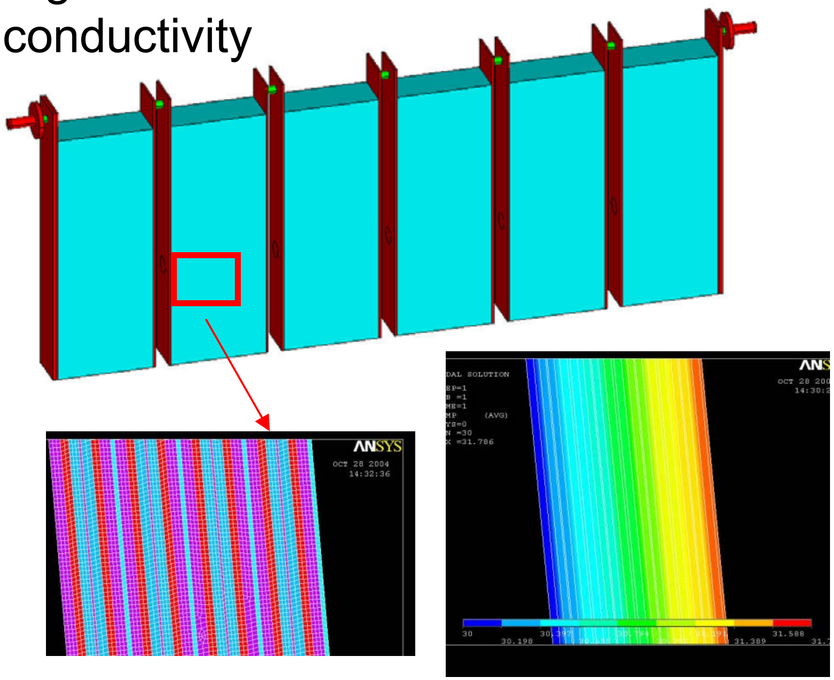


Photo Credits: Matt Keyser & Dirk Long, NREL

http://www.nrel.gov/vehiclesandfuels/energystorage/publications.html

Thermal Conductivity Estimation & Measurement

- Usually case and core of a cell are considered two different regions with different thermal conductivity

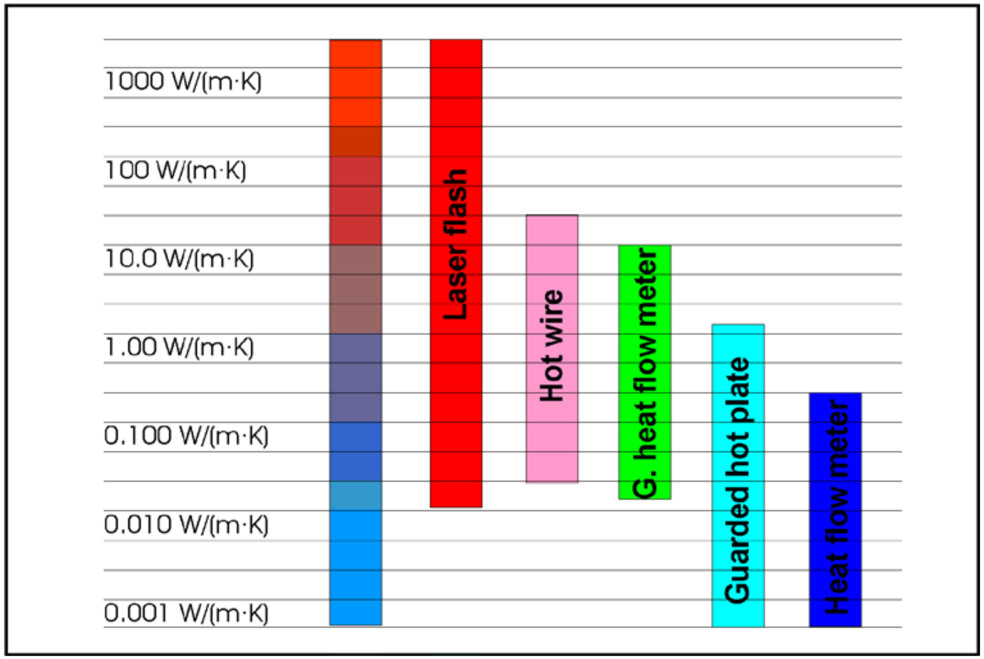


Can use finite element analysis to calculate the effective thermal conductivity in each direction

$k_x = q * \Delta x / \Delta T$
$k_y = q * \Delta y / \Delta T$
or
$k_z = q * \Delta z / \Delta T$
$k_r = q * \Delta r / \Delta T$

- The core material (electrochemically active part) is assumed to consist of a homogenous material with average properties for resistivity and thermal conductivity, **but with different properties in different directions (orthotropic xyz or rθZ)**

Measurement Techniques



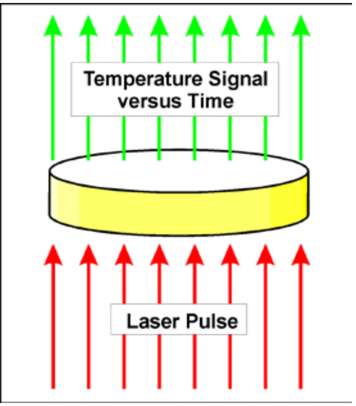
Provided by Peter Ralbovsky - Netzsch Instruments

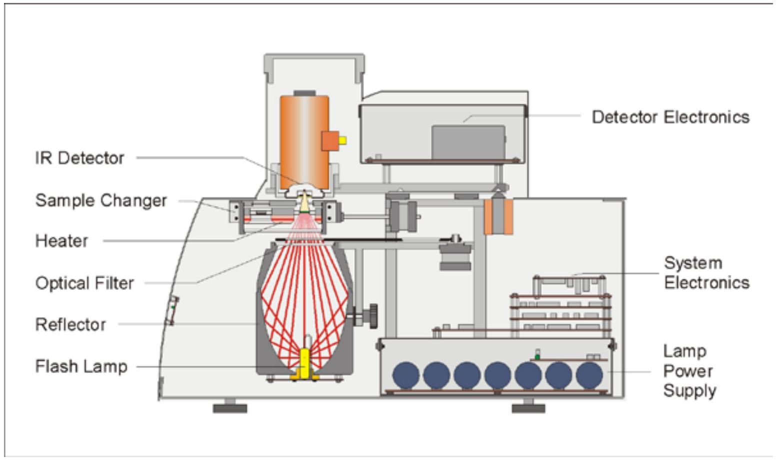
Measuring Thermal Conductivity of LIB Components

Flash Diffusivity Method:

- **Thermal diffusivity (α) is a measure of how quickly a material can change its temperature when heat is applied**
- **The temperature rise on the rear surface is measured in time using an infrared detector**

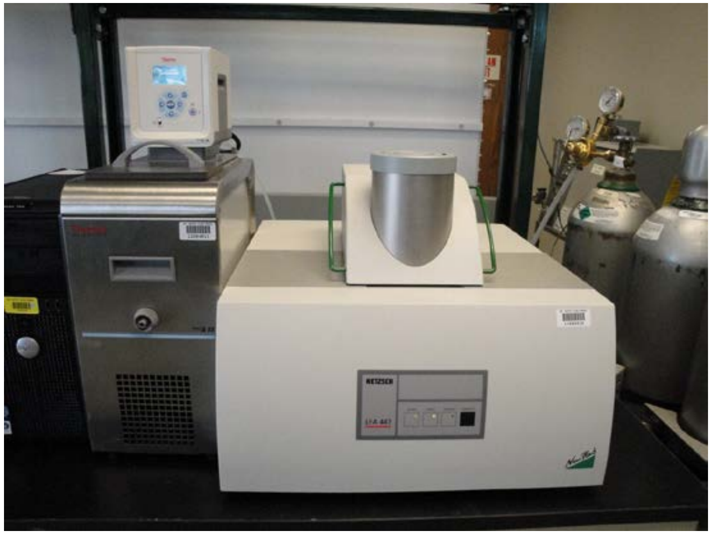
$$K(T) = \alpha(T) \cdot c_p(T) \cdot \rho(T)$$





Provided by Peter Ralbovsky, Netzsch Instruments

Netzsch LFA 447 Unit



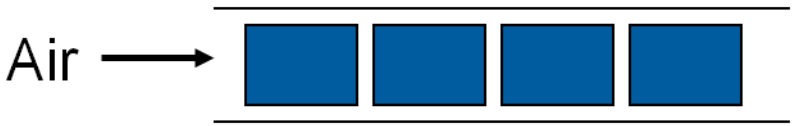
- **Measurements have shown that generally the thermal conductivity of LIB is much lower in-plane than cross-plane**

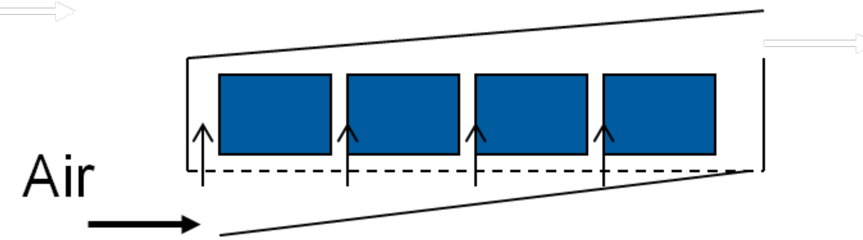
In plane ~ 0.8 to 1.1 W/m/K   Cross plane ~ 28 to 35 W/m/K

Photo Credit: John Ireland, NREL

Battery Thermal Testing Loops

- **Measuring heat transfer coefficients or conductance**





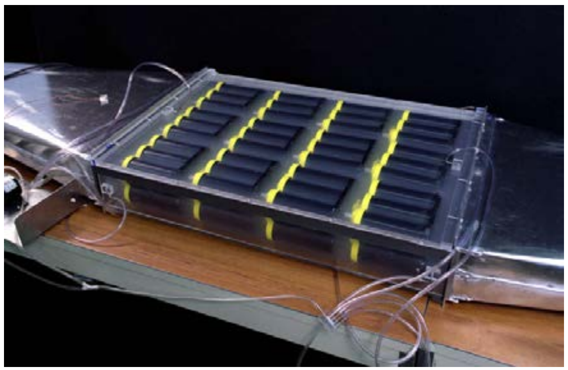
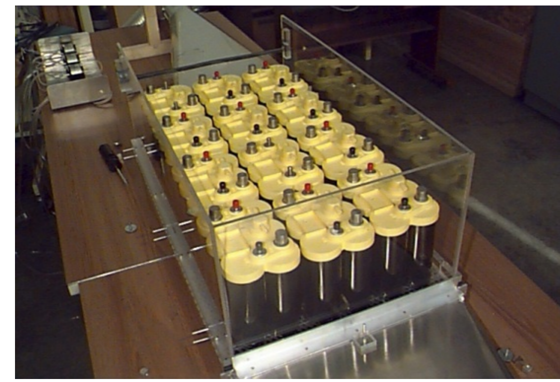
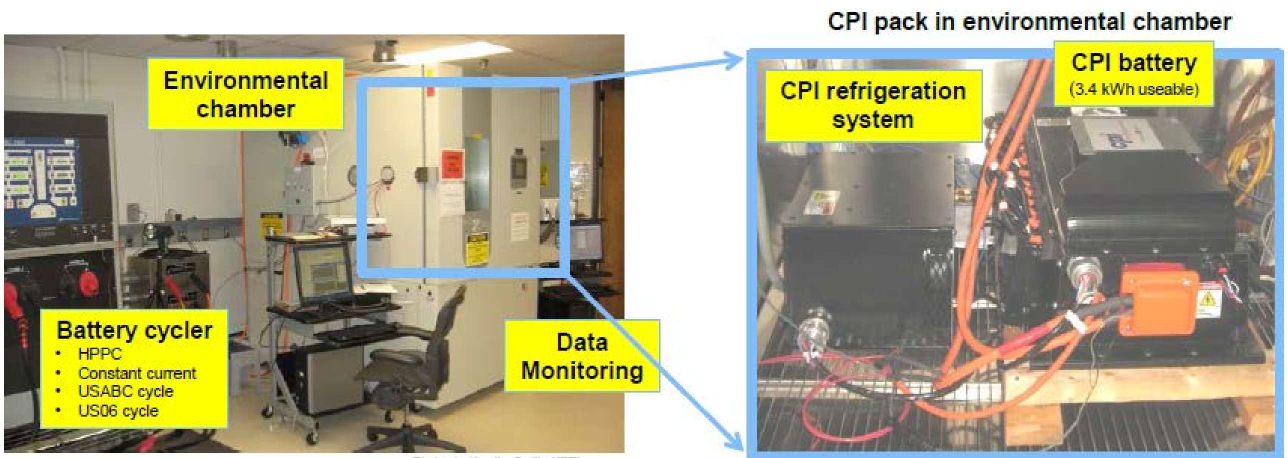


Photo Credits: Ahmad Pesaran



- **Hardware in the loop thermal testing**



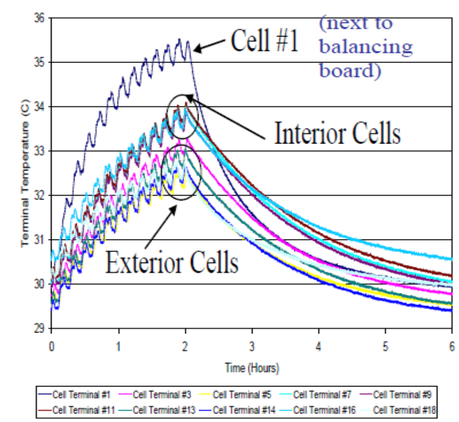
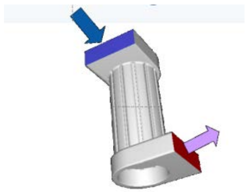


Photo Credits: Kandler Smith, NREL

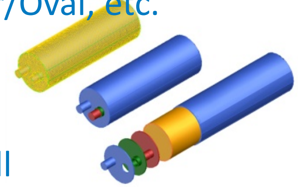
Temp dist. in a USABC module

Process for Battery Thermal Modeling



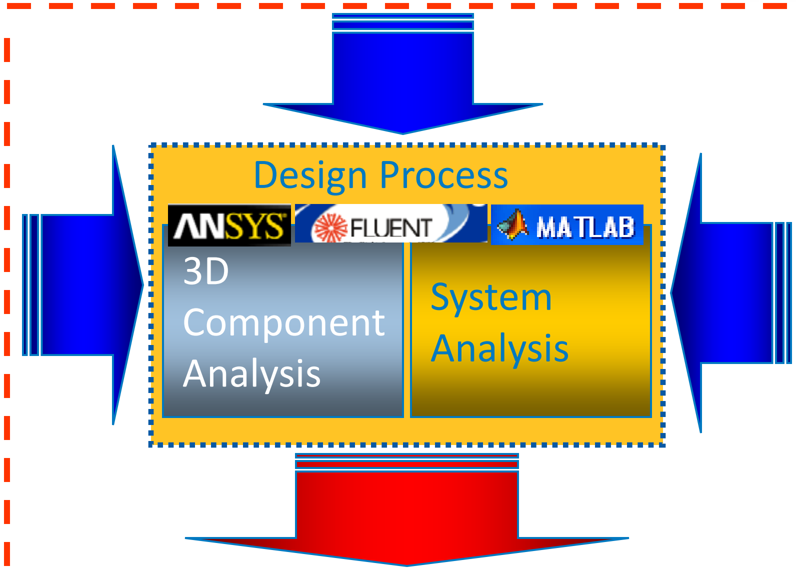
Cell Characteristics

- Shape and size : Prismatic/Cylinder/Oval, etc.
- Materials/Chemistries
- Voltage/current & heat gen data
- Thermal/Current Paths inside a Cell



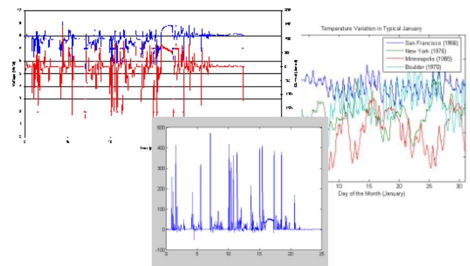
Module Cooling Strategy

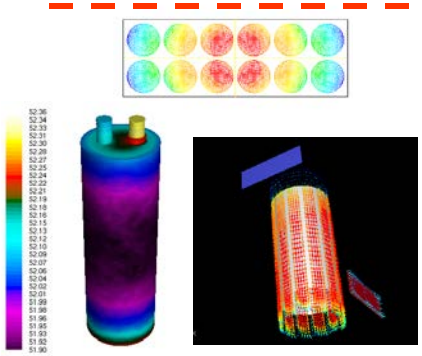
- Coolant Type: Air/Liquid
- Direct Contact/Jacket Cooling
- Serial/Parallel Cooling
- Terminal/Side Cooling
- Module Shape/Dimensions
- Coolant Path inside a Module
- Coolant Flow Rate
- Passive with phase change
- etc.



Operating Conditions

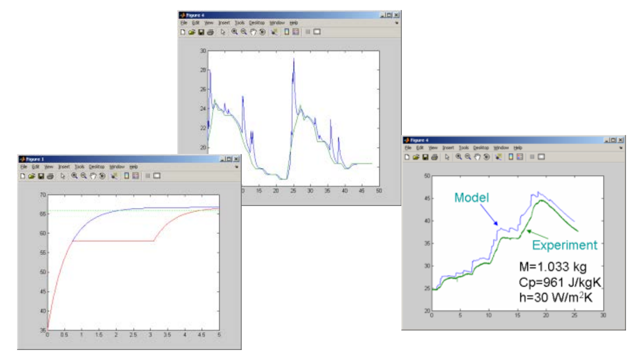
- Vehicle Driving Cycles
- Control Strategy
- Ambient Temperature
- etc.





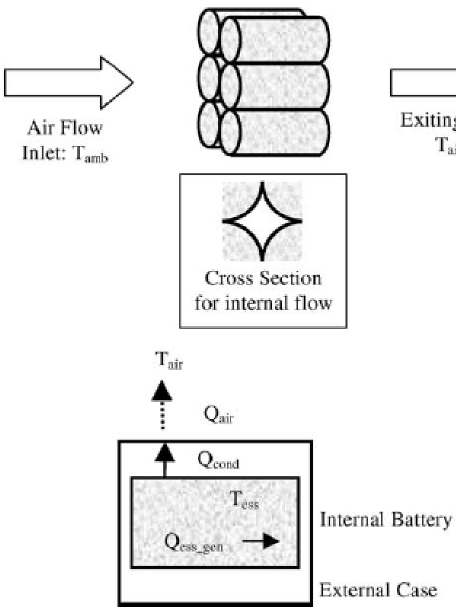
Battery Thermal Responses

- Temperature History Cells/Module/Pack
- Temperature Distribution in a Cell
- Cell-to-Cell Temperature Imbalance in a Module
- Battery Performance Prediction
- Pressure Prop and Parasitic Power
- etc.

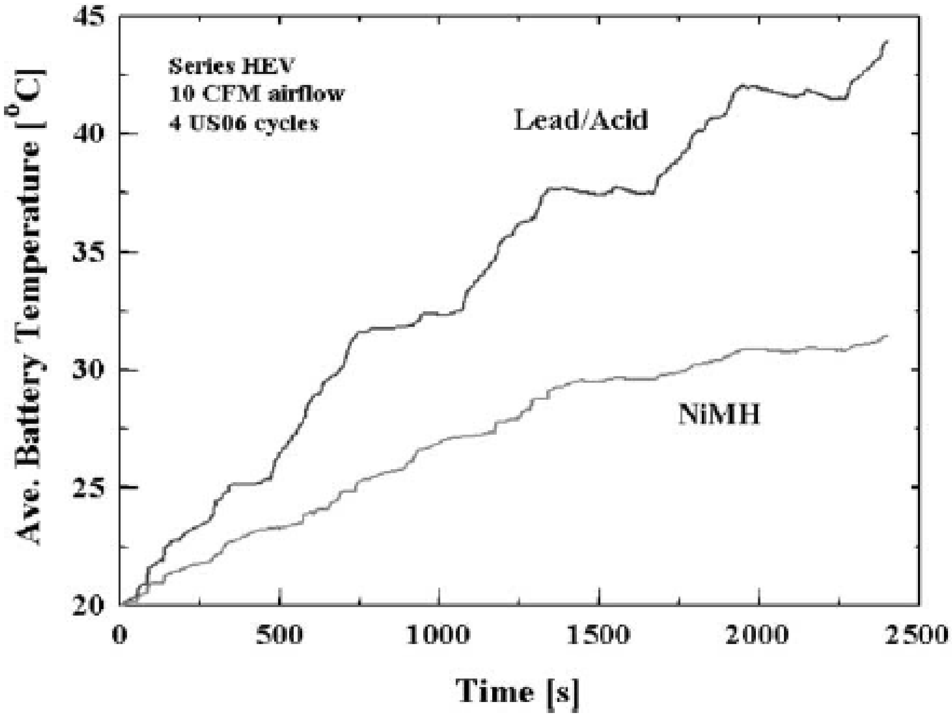


Lumped Capacitance Thermal Model for Vehicle Simulations

- **For vehicle simulation, the thermal model needs to be linked to the battery model for temperature dependency**
- **A 2-node lumped thermal model (case + homogenous core) with simple heat convection is developed for ADVISOR vehicle simulator**



A.A. Pesaran / Journal of Power Sources 110 (2002) 377–382



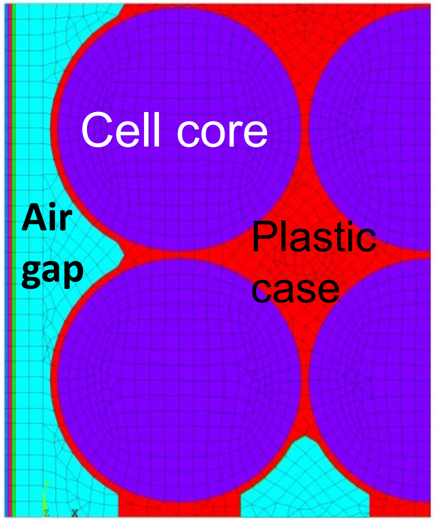
$$Q_{\text{ess\_case}} = \frac{T_{\text{ess}} - T_{\text{air}}}{R_{\text{eff}}} \qquad R_{\text{eff}} = \frac{1}{hA} + \frac{t}{kA}$$

$$T_{\text{air}} = T_{\text{amb}} + \frac{0.5 Q_{\text{ess\_case}}}{\dot{m}_{\text{air}} c_{p,\text{air}}} \quad \text{where } h = \begin{cases} h_{\text{forced}} = a\left(\frac{\dot{m}/\rho A}{5}\right)^b, & T_{\text{ess}} > \text{ess\_set\_tmp} \\ h_{\text{natl}} = 4, & T_{\text{ess}} \le \text{ess\_set\_tmp} \end{cases}$$

$$T_{\text{ess}} = \int_0^t \frac{Q_{\text{ess\_gen}} - Q_{\text{ess\_case}}}{m_{\text{ess}} c_{p,\text{ess}}} \, dt$$

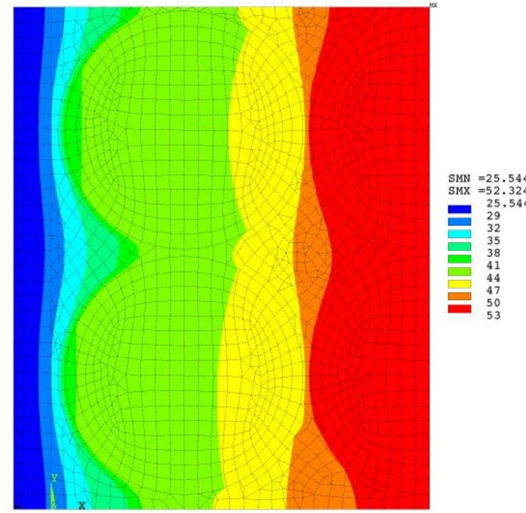
Example of 2-D Module Thermal Modeling

Case 1. No holes and no air flow between cells

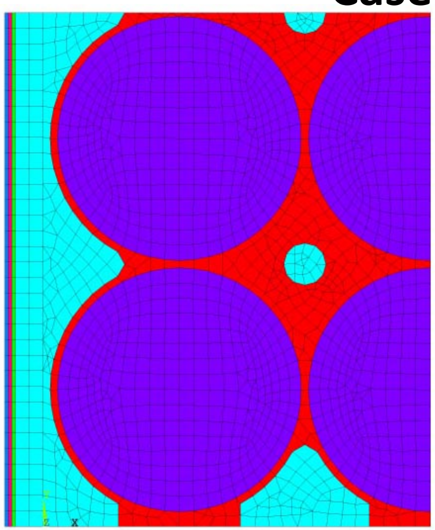


T_{max} = 53°C

Delta T_{core} = 13°C



Case 2. With holes and air flow between cells



T_{max} = 44°C

Delta T_{core} = 9°C

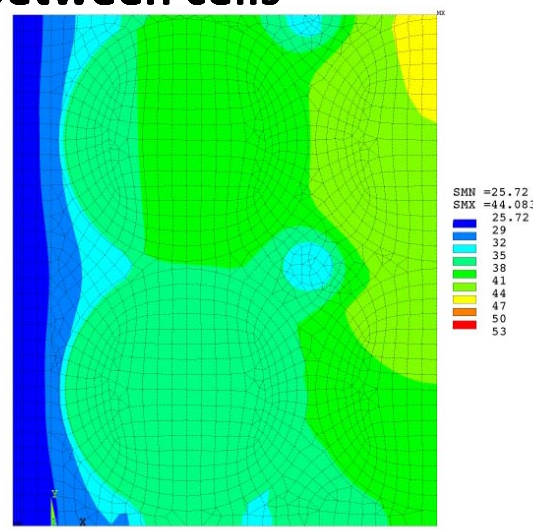
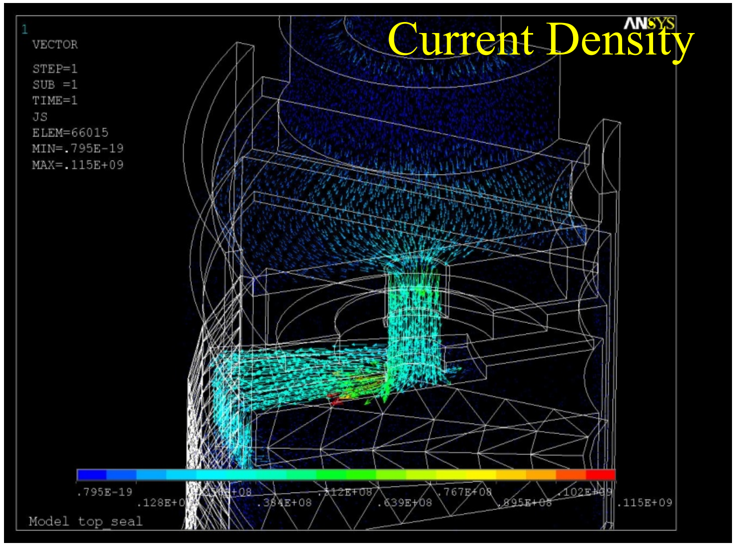
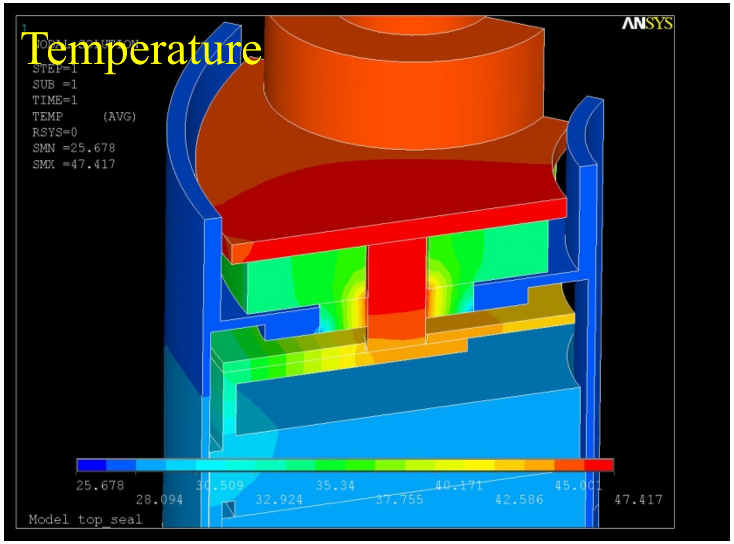


Photo Credits: David Parsons, NREL

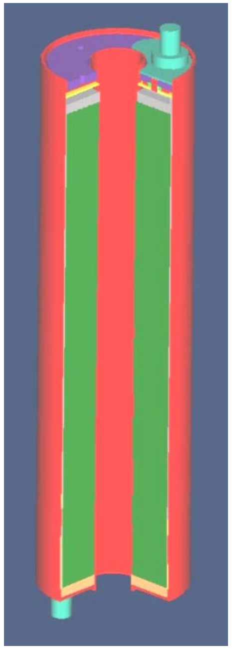
Electro-Thermal Analysis Approach

- Capture details of a cell including non-electrochemical hardware with finite element analysis
- Estimate component resistances using geometry and materials
- Apply voltage drop to calculate current density in components
- Estimate resistive heating (I^2R) in each component
- Apply electrochemical heat of reactions in the core (active parts)
- Apply heat transfer boundary conditions on cell exterior
- Predict temperature distribution in the cell from current density and related heat generation distribution



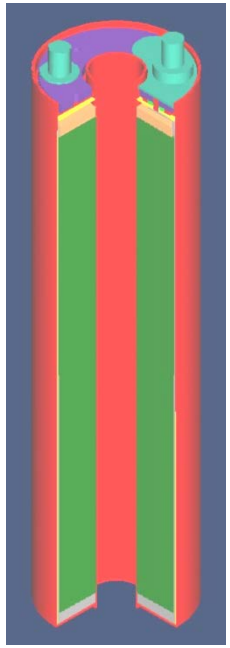


Example of 3-D Electro-Thermal Modeling



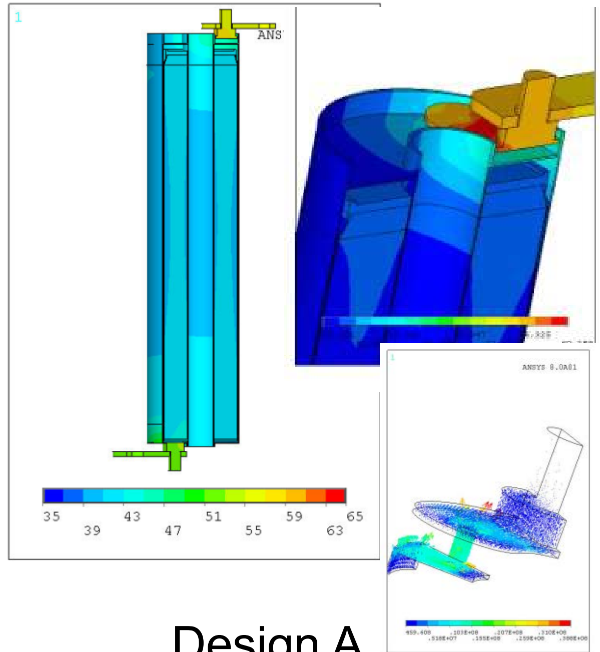
Design A
Terminals on each side

16 Ah
Power Cell

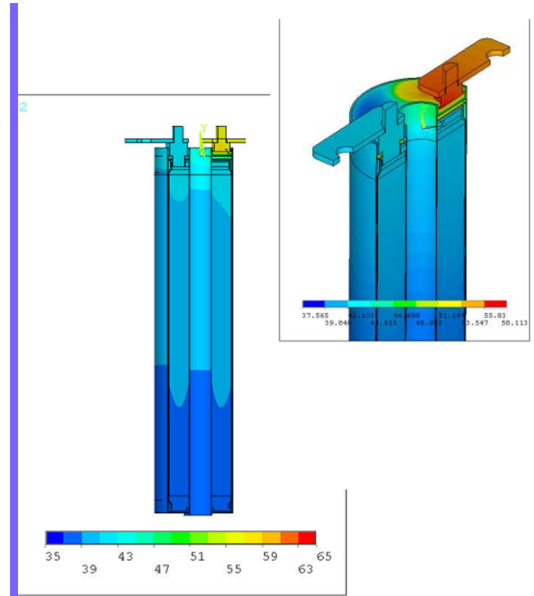


Design B
Terminals on the same side

Photo Credit: Ahmad Pesaran



Design A
Thermal Response



Design B
Thermal Response

Under 110 A RMS load

Dist Design A

Temperature (°C)	Cell Design A			Cell Design B		
Current	110 Amps	166 Amps	5 cycles of Table 3	110 Amps	166 Amps	5 cycles of Table 3
Maximum Hardware	60	93	146	58.1	88	128
Maximum Winding	43	53	66	42	50	48
Average Winding	~ 41	~ 49	~ 47	~ 39	~ 45	~ 44

- The overall resistance of Cell Design B is less than Cell Design A
- Under the same current profile, Cell Design B generates less heat and thus performs better thermally

Electro-thermal Analysis of Lithium Ion Batteries, Pesaran, A.; Vlahinos, A.; Bharathan, D. Proceedings of the 23rd International Battery Seminar, Fort Lauderdale, Florida. March 13-16, 2006.

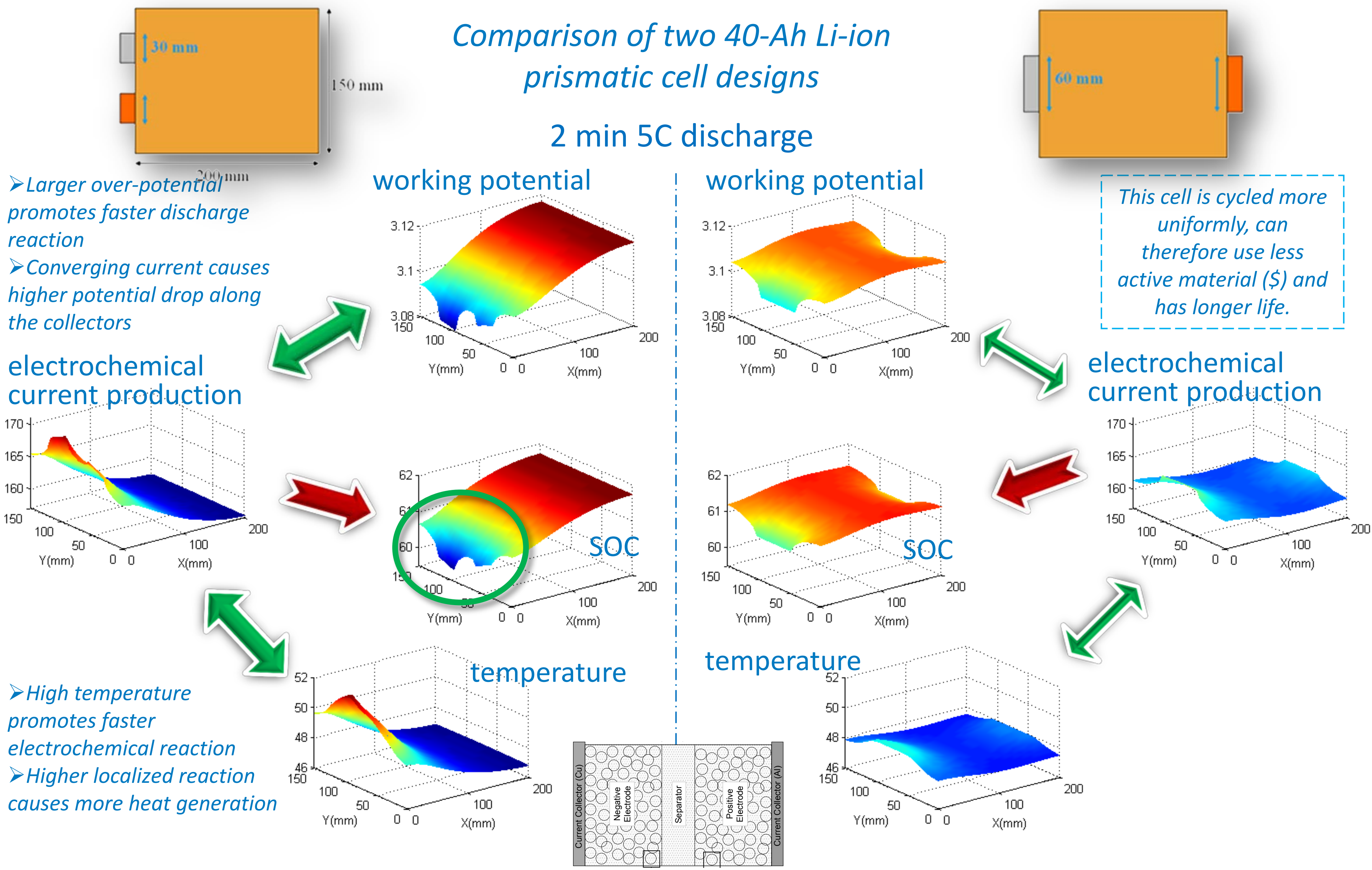
Combined 3D Electrochemical-Thermal Models

Comparison of two 40-Ah Li-ion prismatic cell designs

2 min 5C discharge

- *Larger over-potential promotes faster discharge reaction*
- *Converging current causes higher potential drop along the collectors*

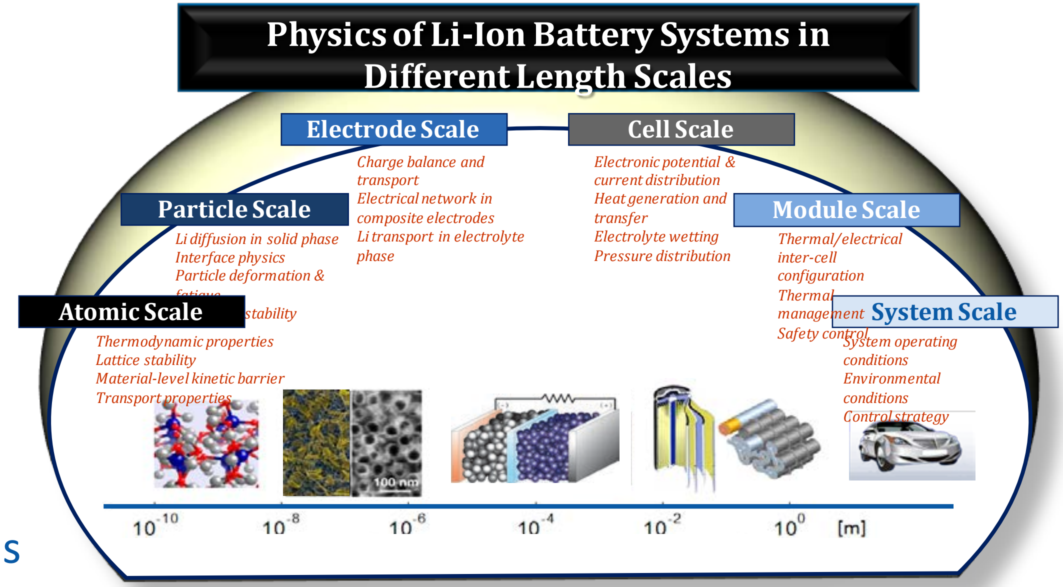
This cell is cycled more uniformly, can therefore use less active material ($) and has longer life.

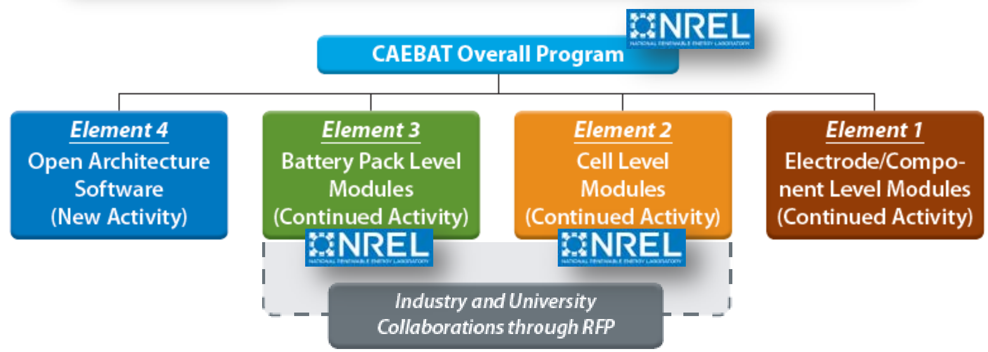


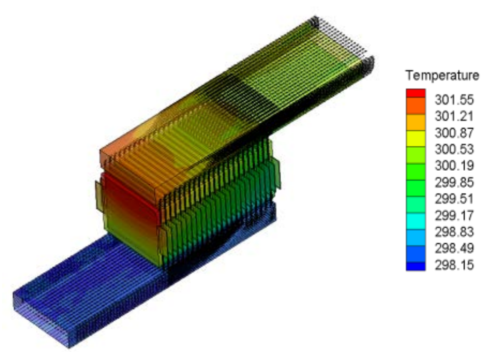
- *High temperature promotes faster electrochemical reaction*
- *Higher localized reaction causes more heat generation*

Computer-Aided Engineering of Batteries (CAEBAT)

- U.S. Department of Energy is supporting development of electrochemical-thermal models and software design
- The objective is to shorten time and reduce cost for design and development of battery systems, including the design and analysis of BTMSs
- Other software design and analysis tools dealing with other physics may be incorporated in CAEBAT







Thermal-electrochemical response of a pack
Courtesy of Christian Shaffer, EC Power-CAEBAT

GM ANSYS
CD-adapco BD A123 SYSTEMS Johnson Controls
PENNSTATE EC POWER Ford Johnson Controls

Summary

- Battery thermal management needed for xEVs
- Battery thermal management system needs to be optimized with right tools for lowest cost
- NREL has state-of-the art experimental and analytical tools for analysis and design of battery thermal management systems
- Experimental tools, such as the isothermal calorimeter, are essential for obtaining data for generating input to design tools and eventually verifying the performance of the battery thermal management system
- Computer-aided engineering tools for the design of battery electrical and thermal management systems are now accessible to automotive and battery engineers

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  - Christian Shaffer (EC Power)
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  - Mark Mihalic
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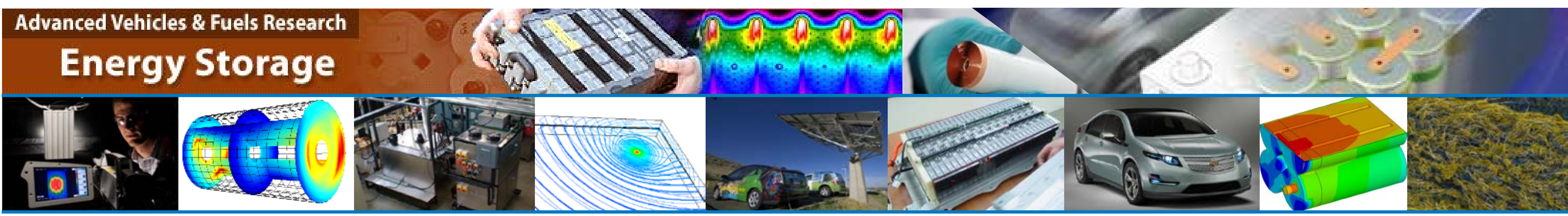

nrel.gov/vehiclesandfuels/energystorage