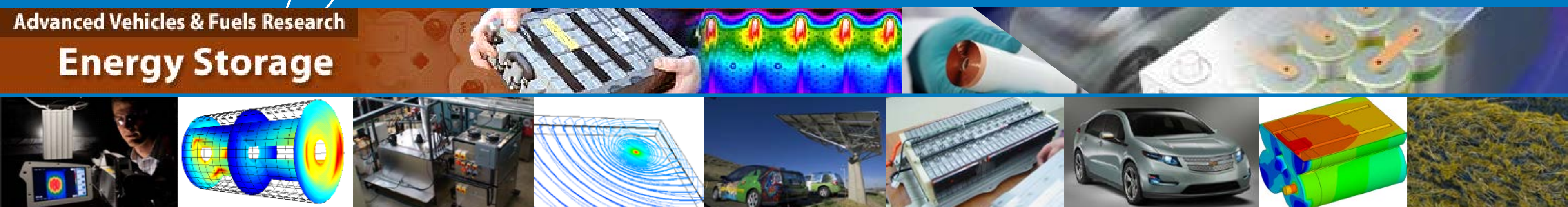
Tools for Designing Thermal Management of Batteries in Electric Drive Vehicles



Ahmad Pesaran, Ph.D.

Matt Keyser, Gi-Heon Kim, Shriram Santhanagopalan, Kandler Smith

National Renewable Energy Laboratory

Golden, Colorado

Presented at the

Large Lithium Ion Battery Technology & Application Symposia

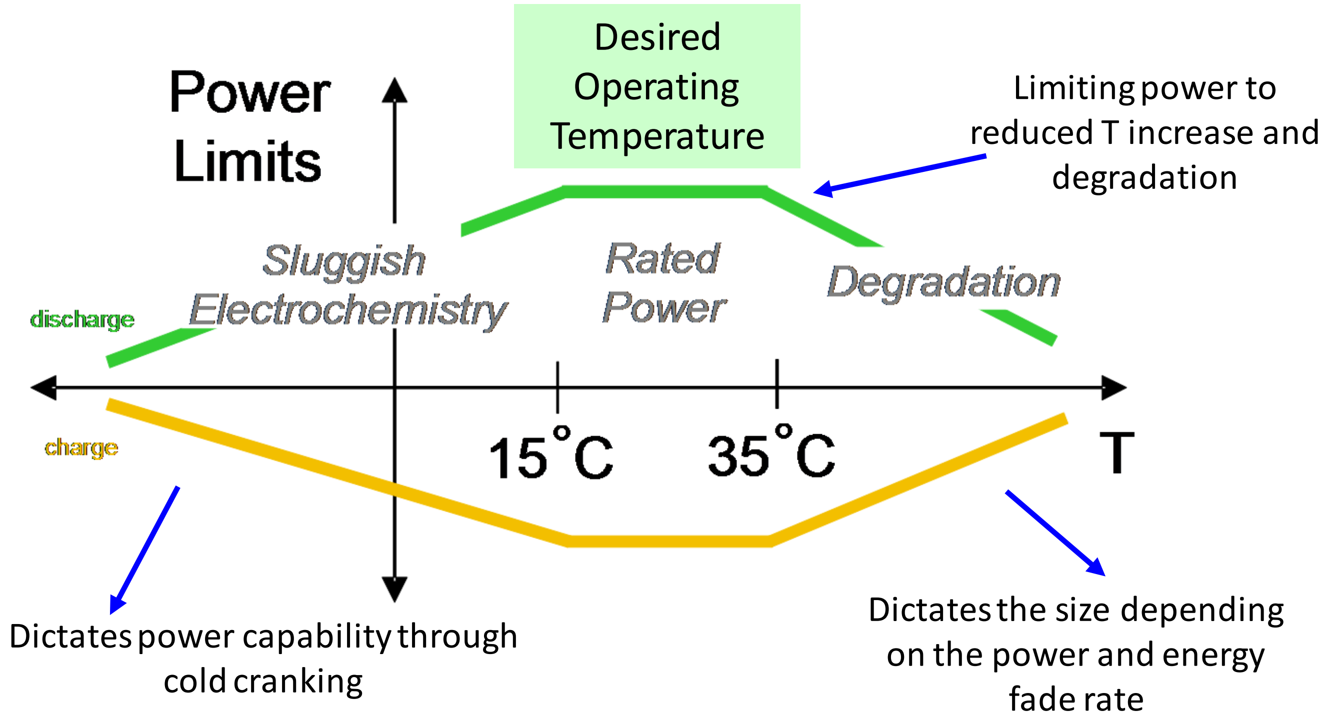
Advanced Automotive Battery Conference

Pasadena, CA • February 4-8, 2013

NREL/PR-5400-57747

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**



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
  - …

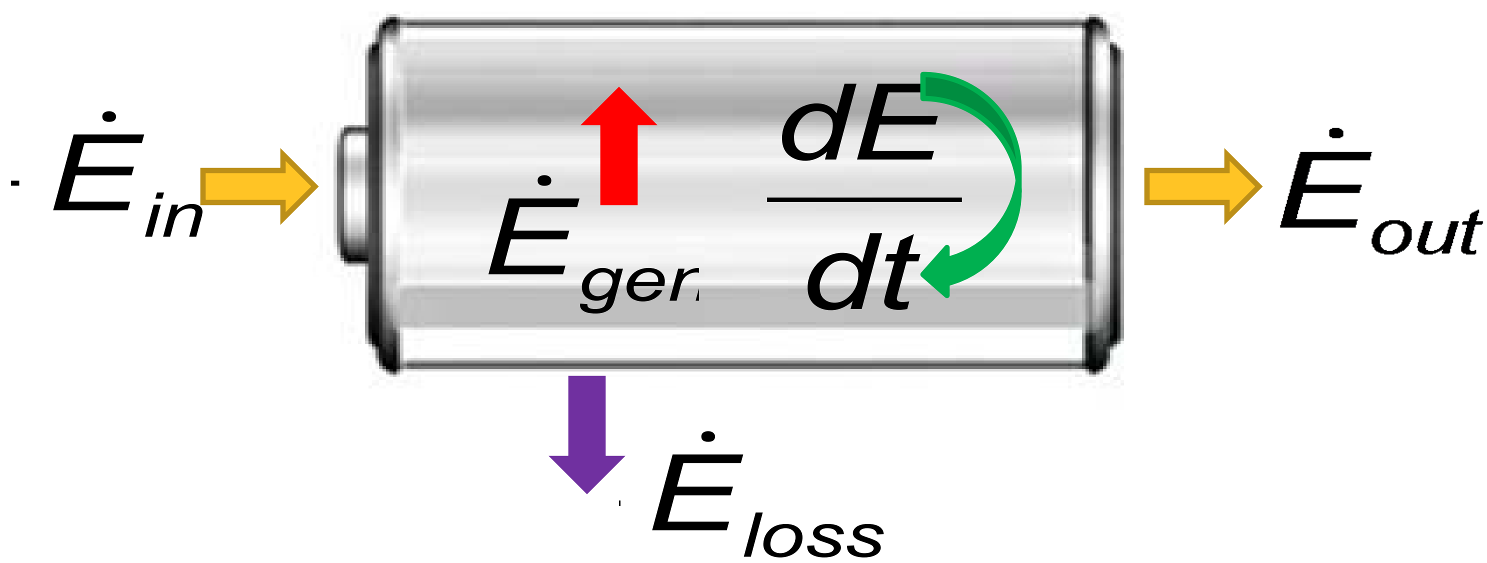
Battery Thermal Management System

- 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

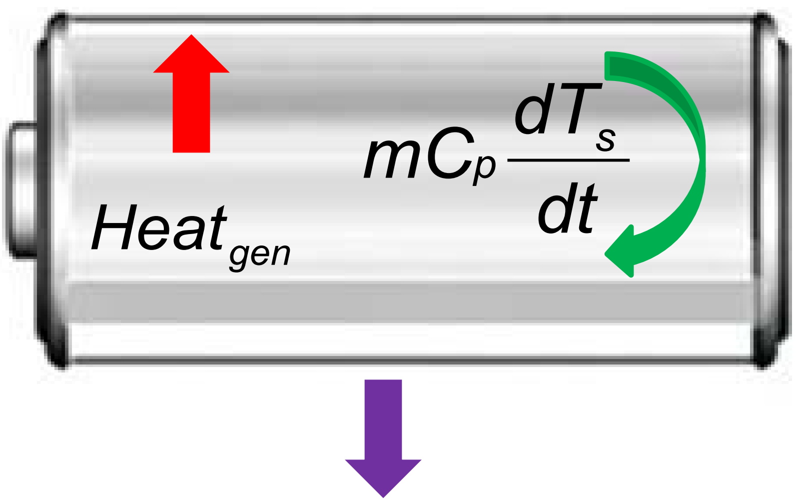


Heat Transfer in a Battery

(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



$$\underbrace{hA(T_s - T_a) + e\delta A(T_s^4 - T_a^4) + Q_{Ext\_conduction}}_{\text{Method of heat rejection/addition for thermal control}}$$

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

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

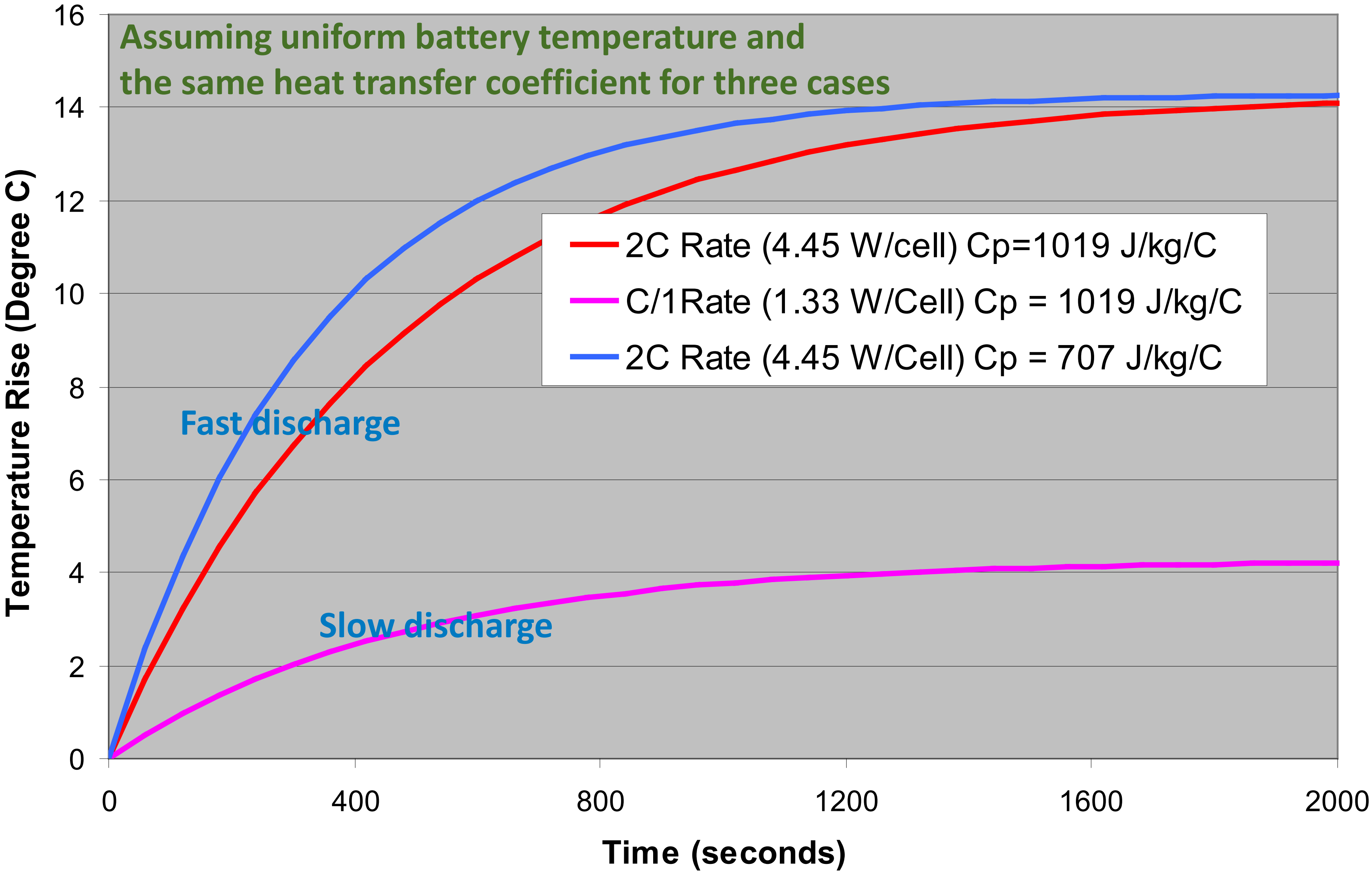
D. Bernardi, E. Pawlikowski and J. Newman

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

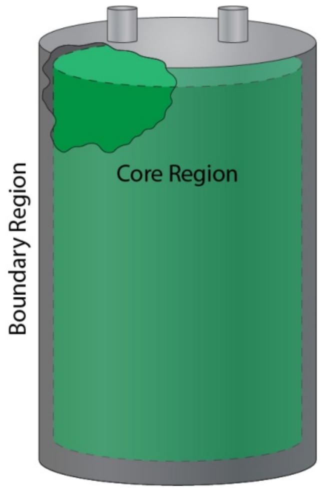
T_s = Battery Temp

T_a = Ambient Temp

Heat Generation Rate and Specific Heat Impact Battery Temperature Rise



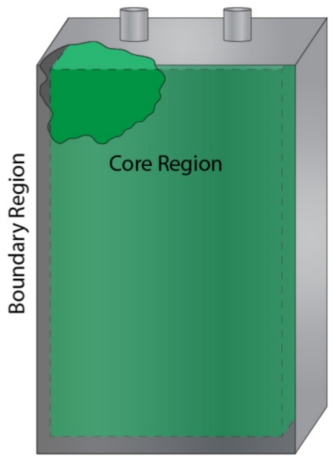
Heat Transfer in a Battery
(Non-isothermal; case and core regions)



Core region

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

k : *thermal conductivity*



Case or boundary region

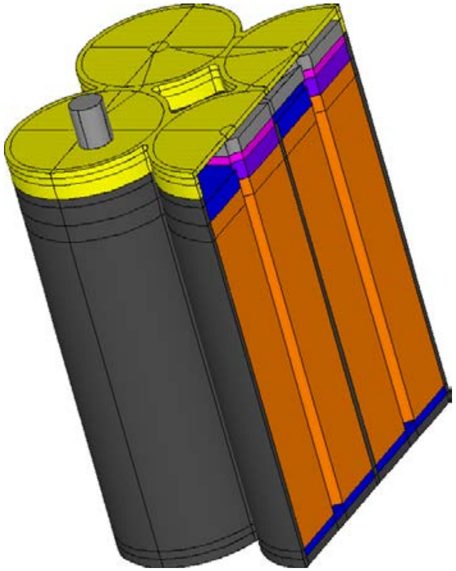
$$-k_n \frac{\partial \mathrm{T}(n)}{\partial n}\bigg|_{n=0,L} = h(T_s - T_\infty) + e\delta(T_s^4 - T_\infty^4) + \rho_B C_{p,B} H_B \frac{\partial T_B}{\partial t}$$

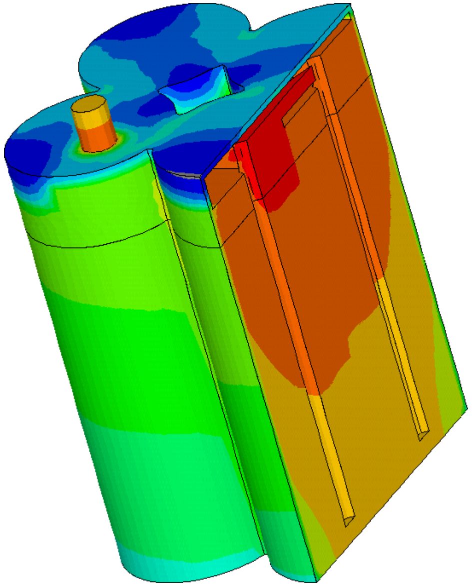
Heat flux from the core | Convection from various case surfaces | Radiation from various case surfaces | Heat accumulation in the case

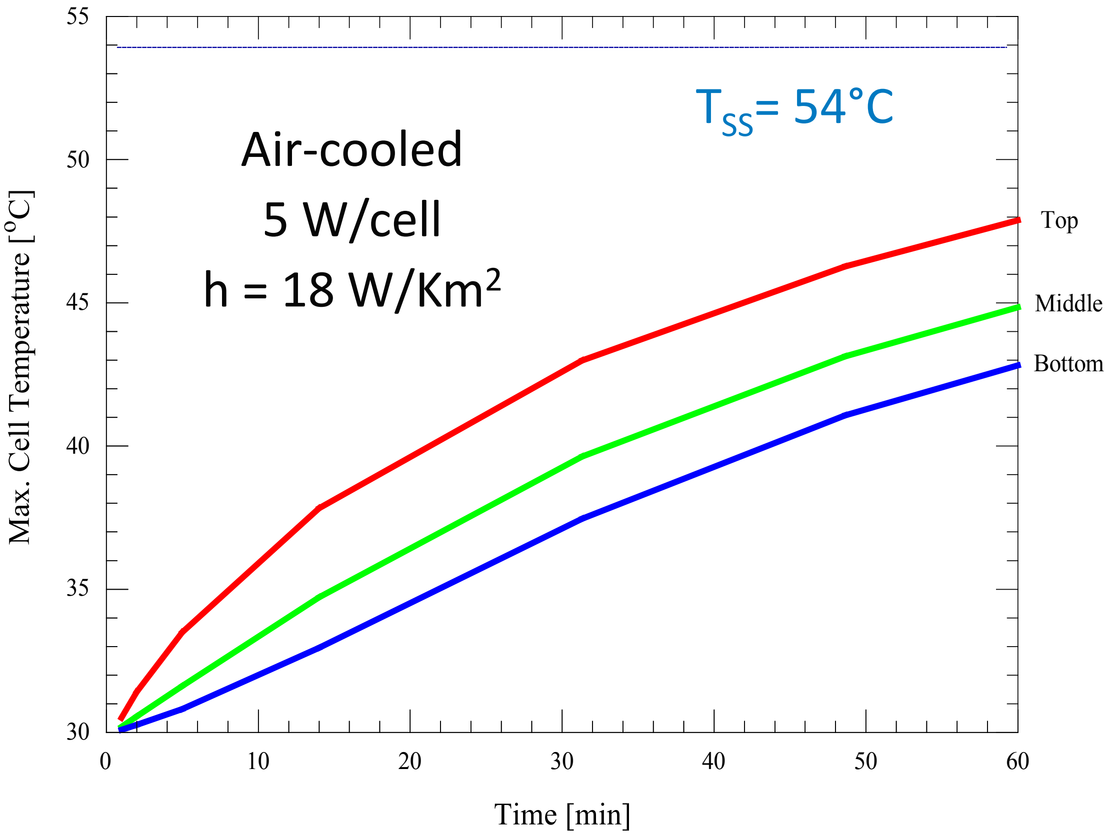
Johnsee Lee, K. W. Choi, N. P. Yao and C. C. Christianson

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**

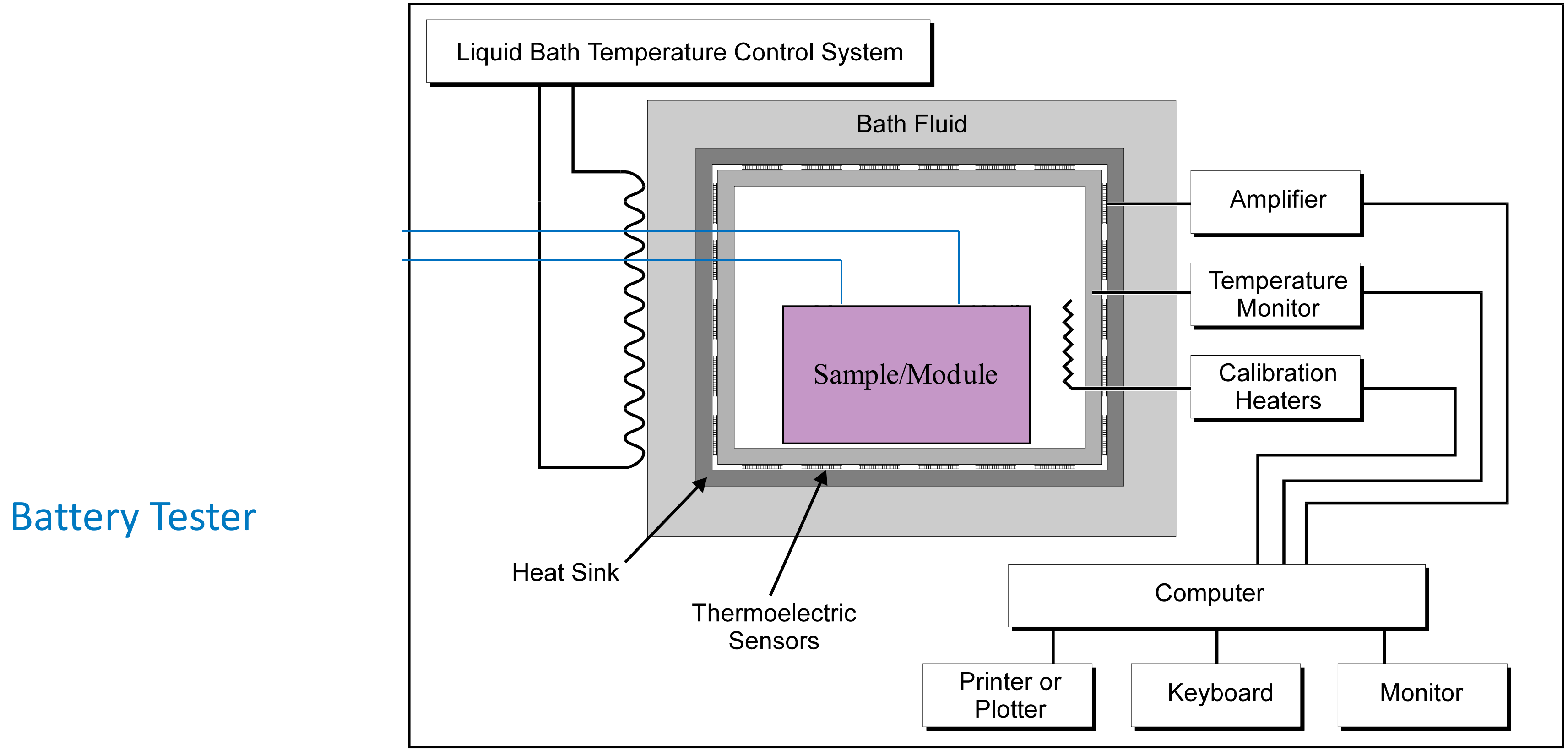
Tools for Designing BTMS

- **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)



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

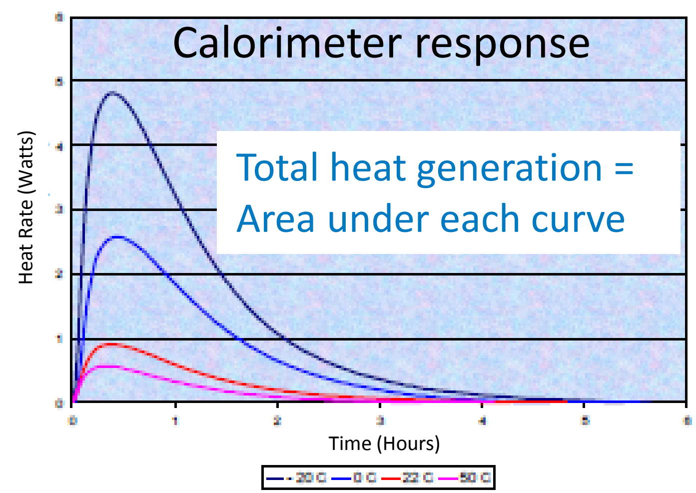
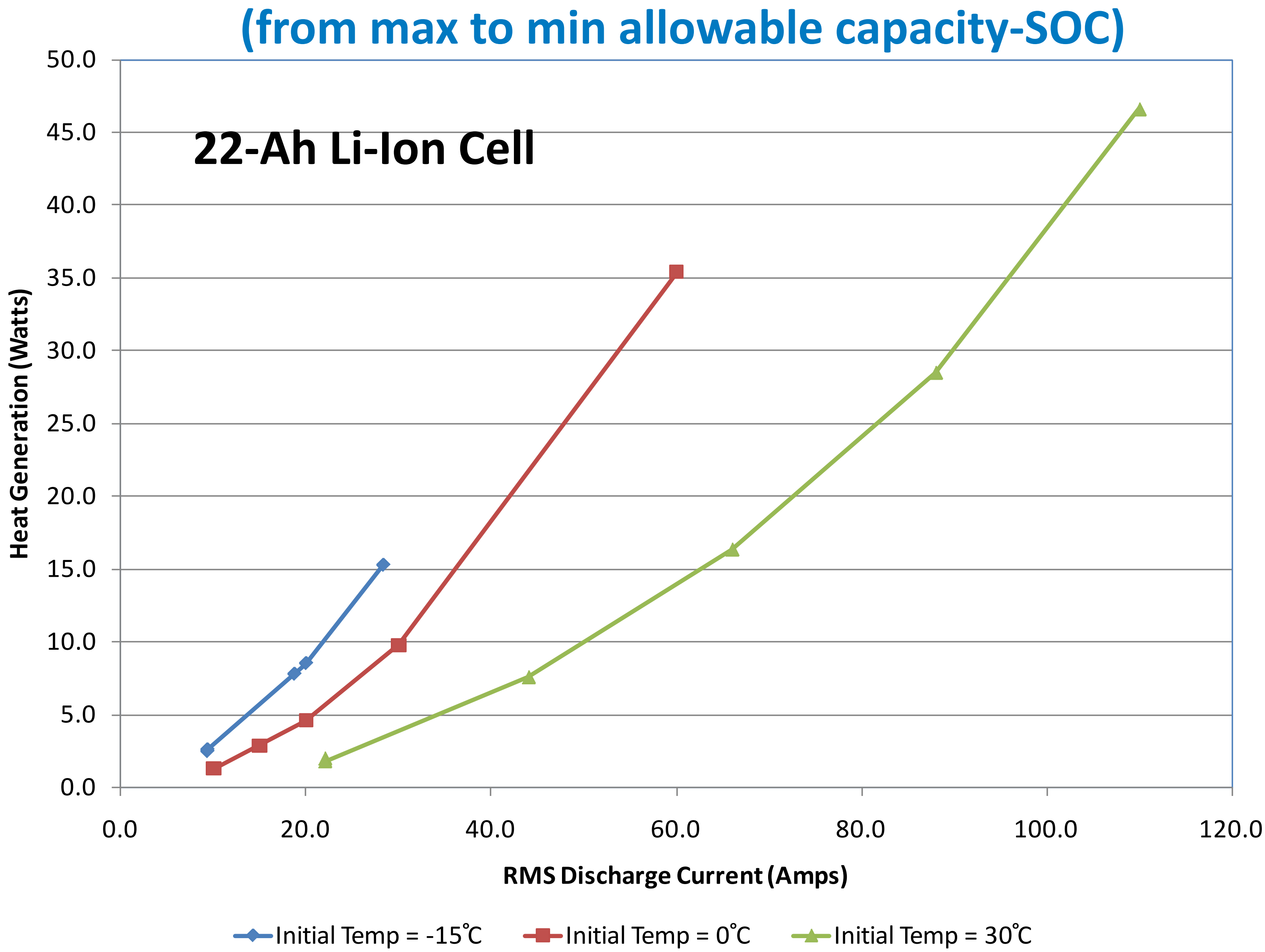


Photo Credits: David Parson & Matt Keyser, NREL

Example Heat Generation Data for CC Discharge



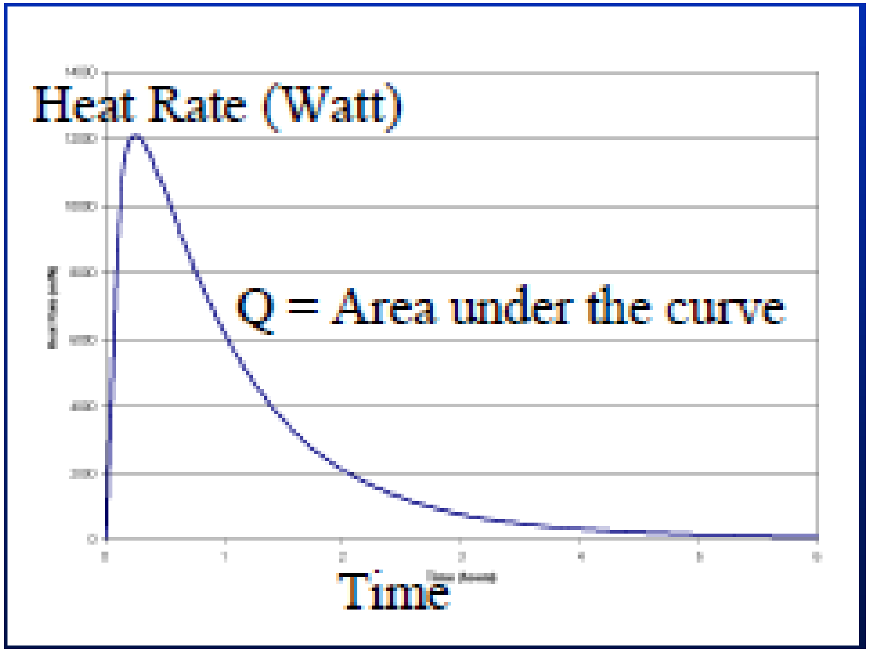
Specific Heat (Heat Capacity)

- **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

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



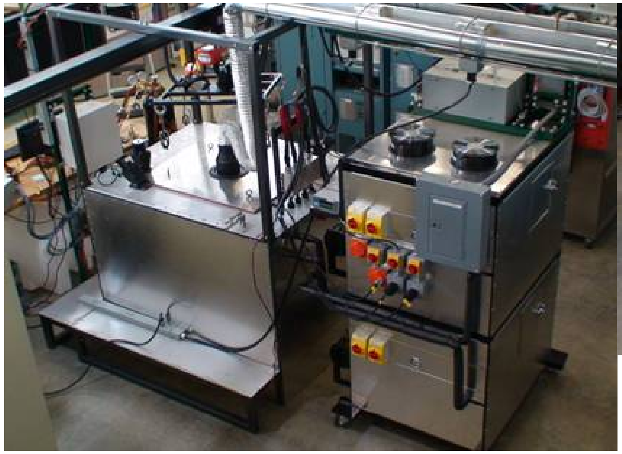
Cell/Module	$T_{average}$ (°C)	Heat Capacity J/kg/°C
NiMH – 18 Ah	33.2	677
Li-Ion 18650	33.1	1,105
Li-Ion Pouch – 4 Ah	18	1,012
VRLA – 16.5 Ah	32	660
Ni Zn – 22 Ah	20	1,167

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%**

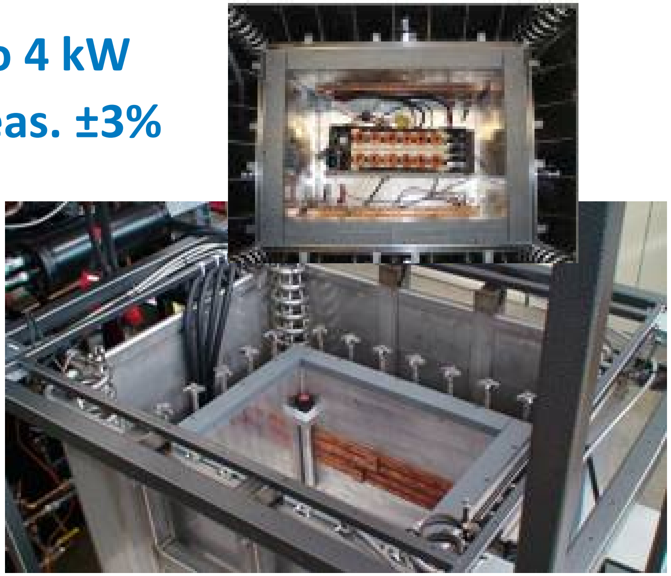
Photo Credits: Dennis Schroder & Ahmad Pesaran, NREL



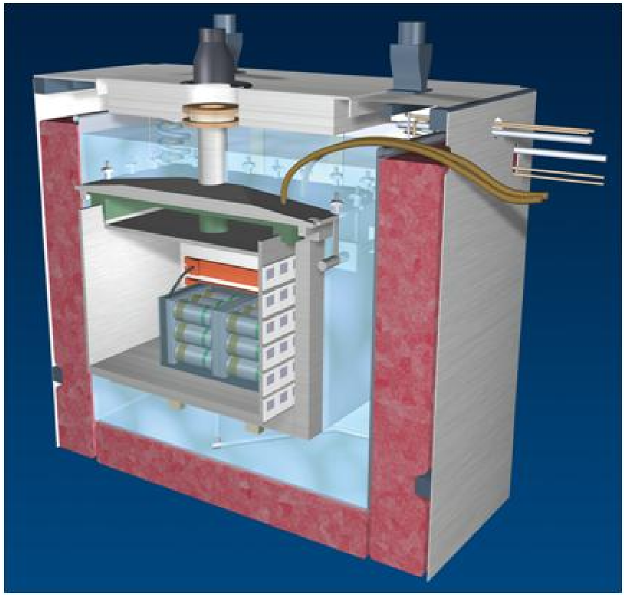
Completed System with Heating/Cooling Unit

Test Chamber

Flux Gauges in Test Chamber



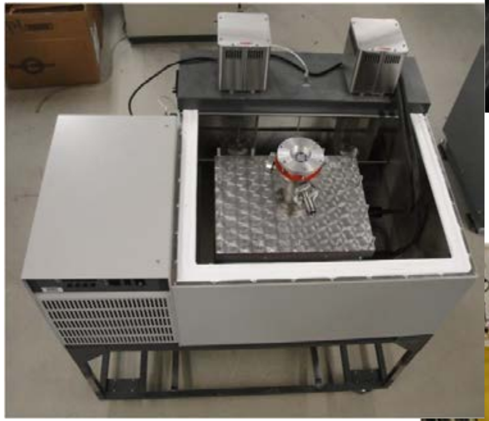
Test Chamber in Isothermal Bath



NREL's New Isothermal Cell Calorimeter

Photo Credits: Dennis Schroder & Dirk Long, NREL

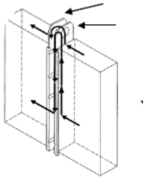
- Single chamber, conduction, isothermal
- Test chamber submerged under isothermal bath
- Testing chamber: 15 cm W x 10 cm L x 6 cm H
- Heat detection limit: 1 mW and 10 J
- Initial testing shows excellent baseline stability and an error of less than ±1.6%
- CRADA and license agreement signed with NETZSCH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

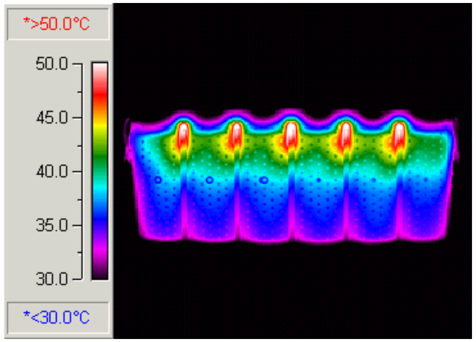


http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/50558.pdf

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

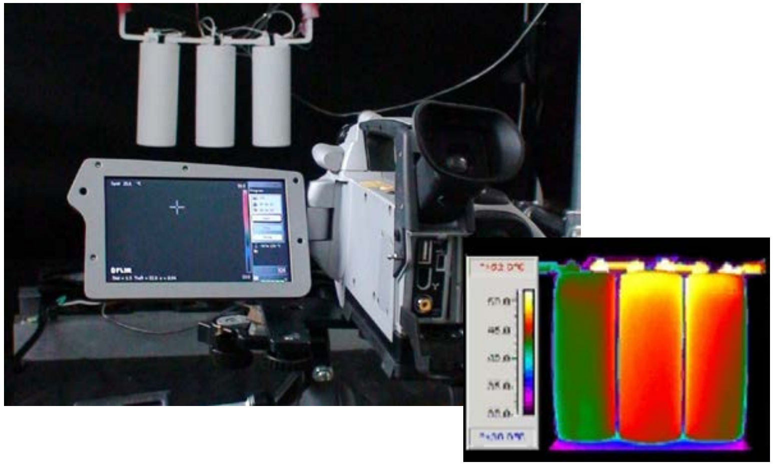
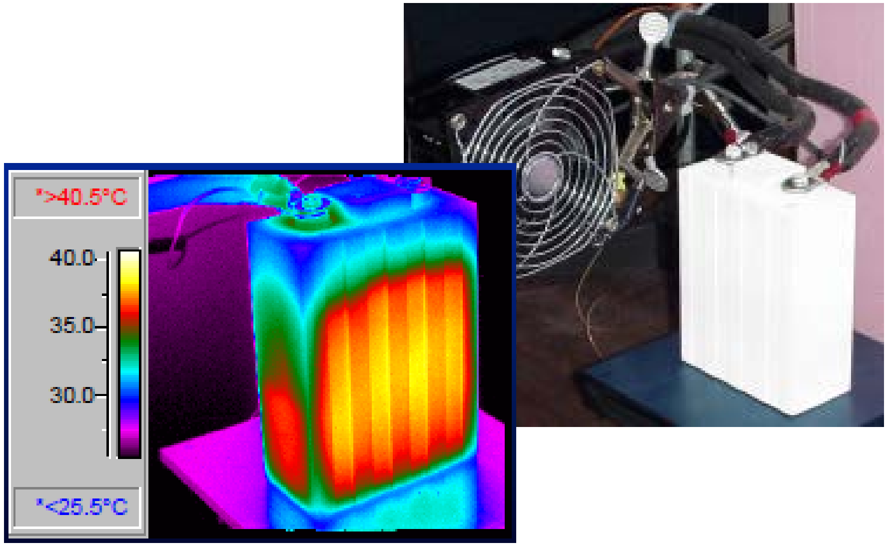
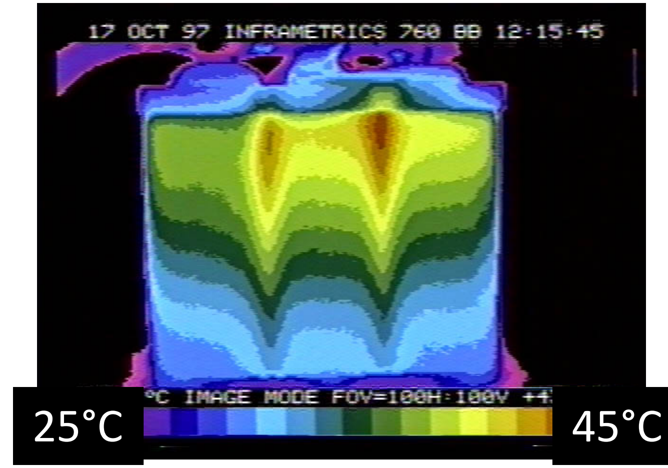
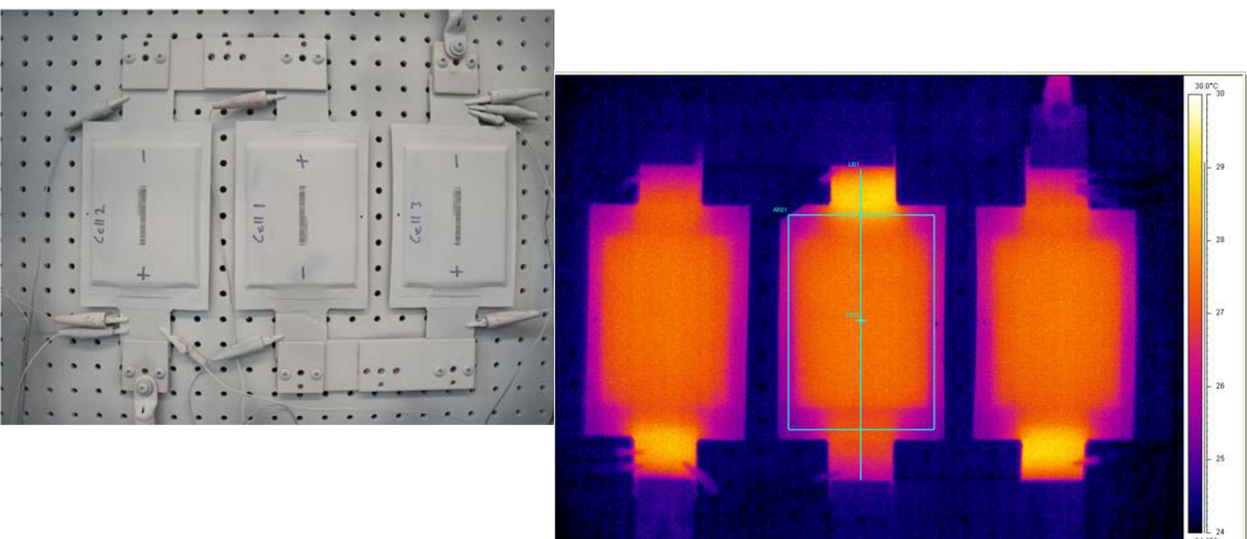


Photo Credits: Matt Keyser, NREL

Examples of Battery Infrared Thermal Imaging







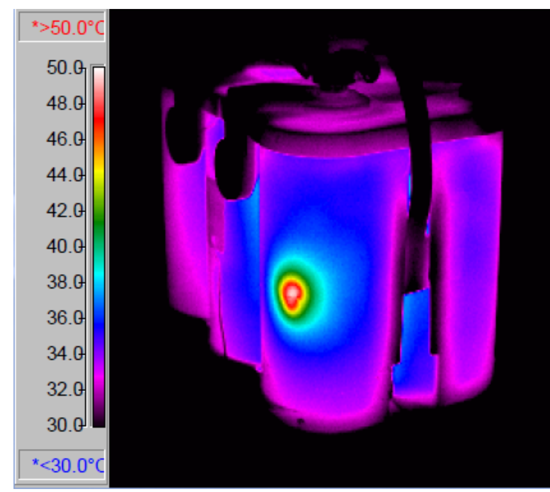
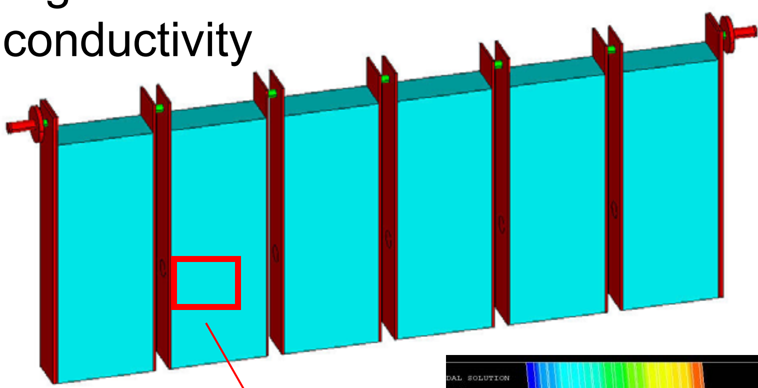


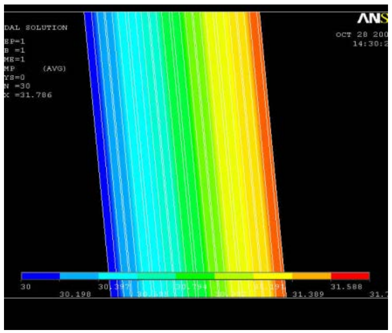
Photo Credits: Matt Keyser & Dirk Long, NREL

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



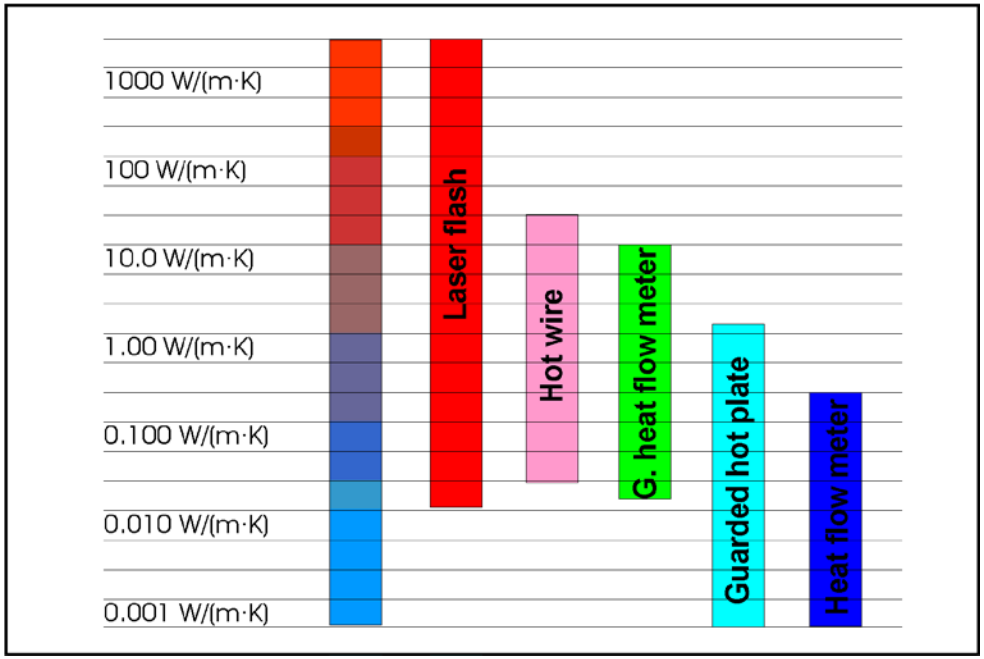


Can use finite element analysis to calculate the effective thermal conductivity in each direction

$k_x = q * \Delta x / \Delta T$
$k_y = q * \Delta y / \Delta T$
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



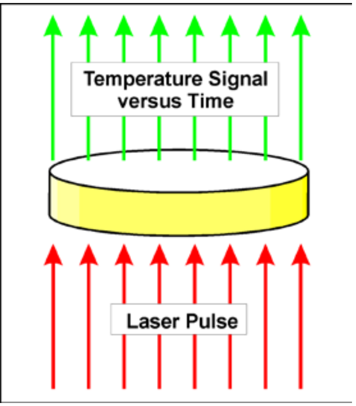
Provided by Peter Ralbovsky - Netzsch Instruments

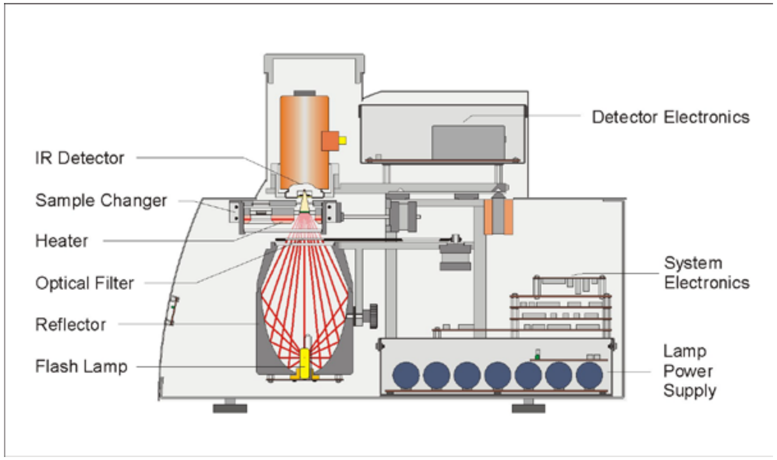
Measuring Thermal Conductivity of LIB Components

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

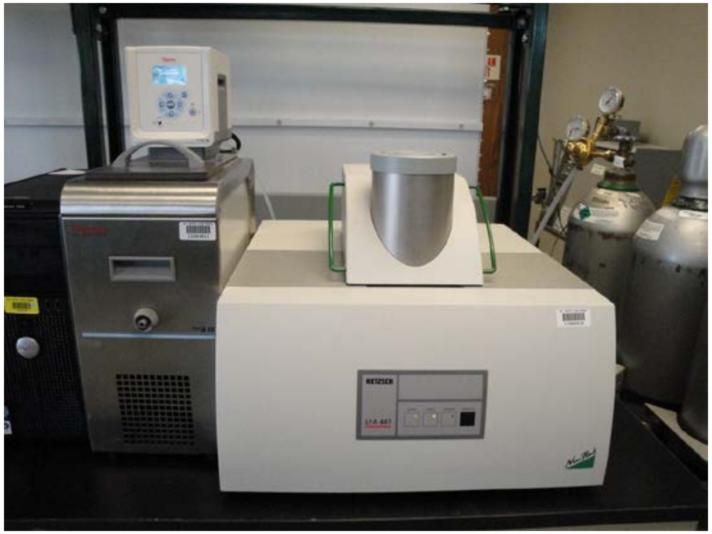
$$K(T) = \alpha(T) \cdot c_p(T) \cdot \rho(T)$$





Provided by Peter Ralbovsky, Netzsch Instruments

Netzsch LFA 447 Unit



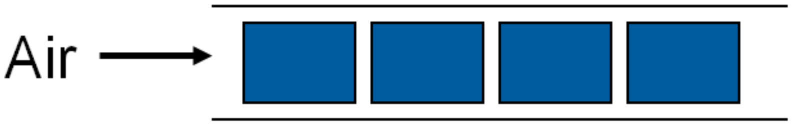
- Measurements have shown that generally the thermal conductivity of LIB is much lower in-plane than cross-plane

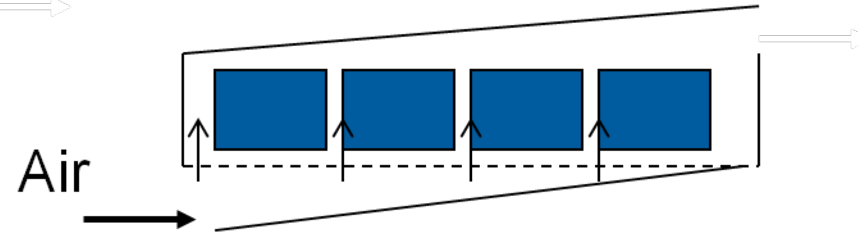
Cross plane ~ 0.8 to 1.1 W/m/K   In plane ~ 28 to 35 W/m/K

Photo Credit: John Ireland, NREL

Battery Thermal Testing Loops

- **Measuring heat transfer coefficients or conductance**





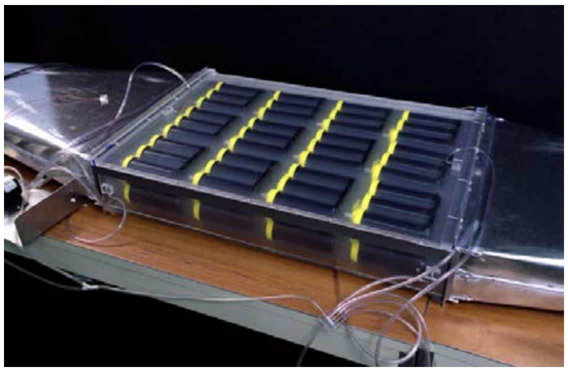
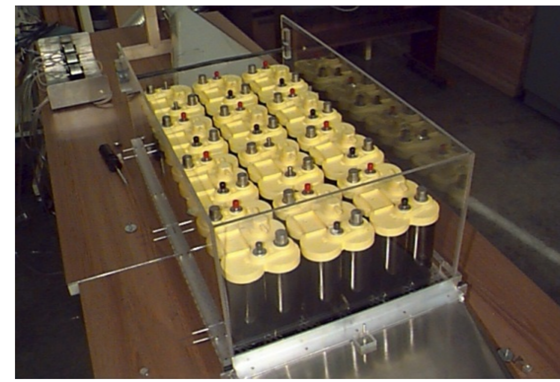


Photo Credits: Ahmad Pesaran



- **Hardware in the loop thermal testing**

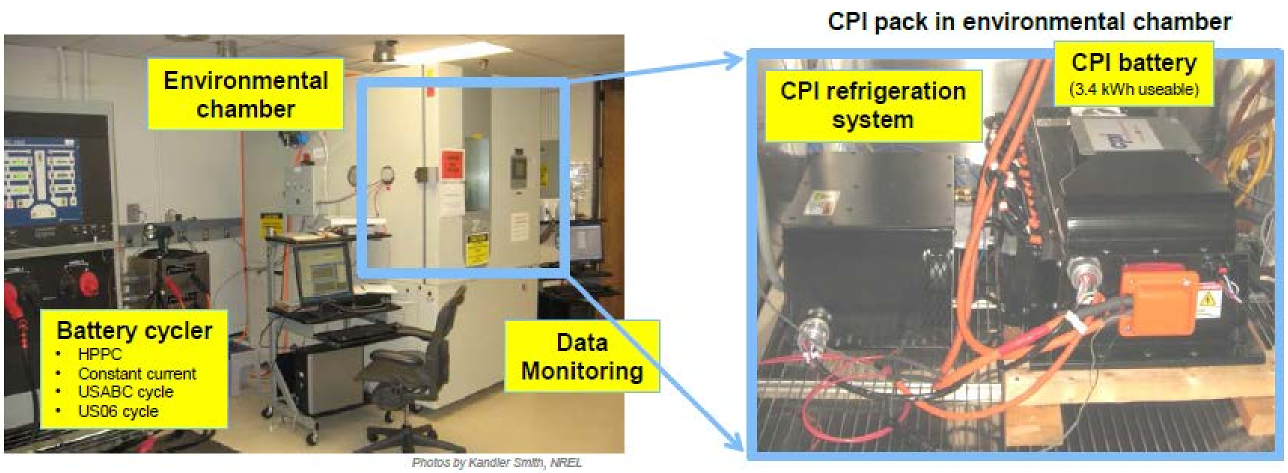
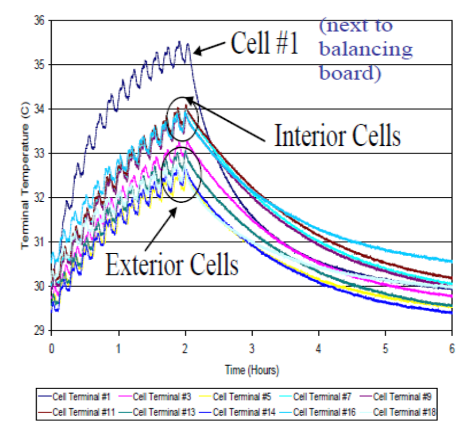
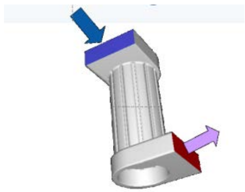


Photo Credits: Kandler Smith, NREL



Temp dist. in a USABC module

Process for Battery Thermal Modeling

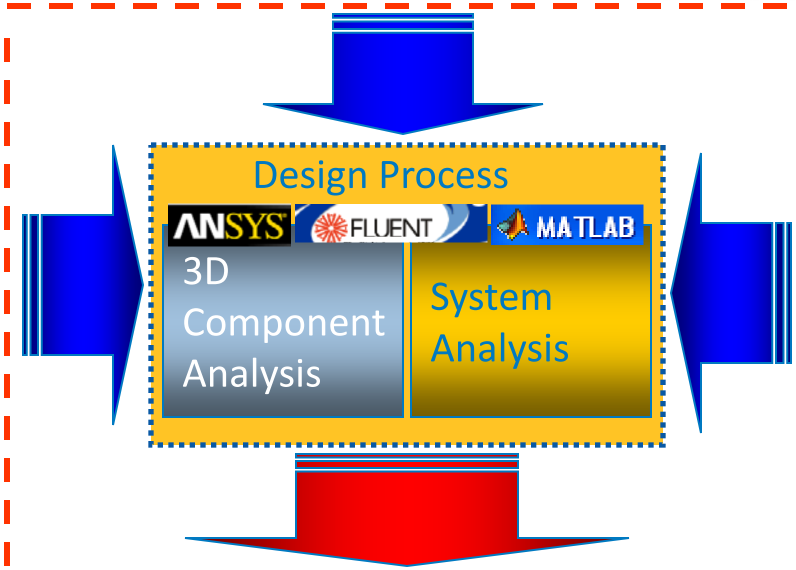


Module Cooling Strategy

- 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.

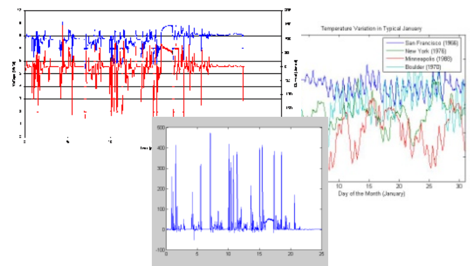
Cell Characteristics

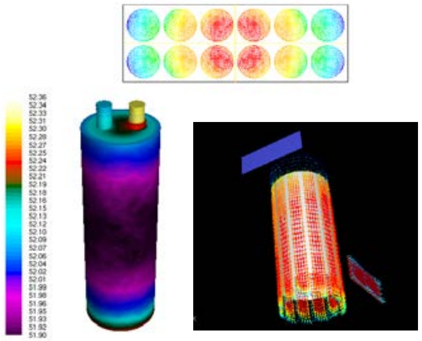
- Shape and size : Prismatic/Cylinder/Oval, etc.
- Materials/Chemistries
- Voltage/current & heat gen data
- Thermal/Current Paths inside a Cell



Operating Conditions

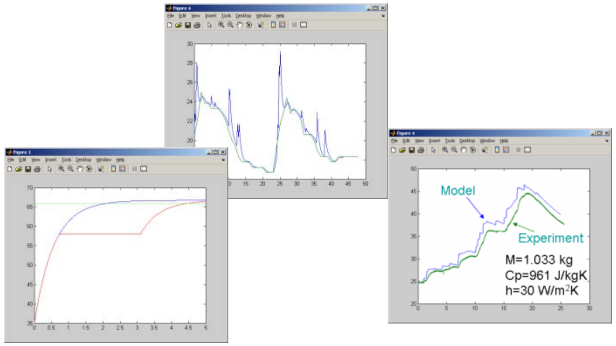
- Vehicle Driving Cycles
- Control Strategy
- Ambient Temperature
- etc.





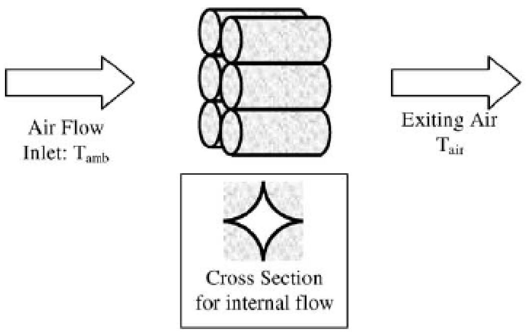
Battery Thermal Responses

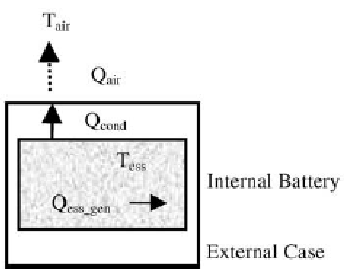
- Temperature History Cells/Module/Pack
- Temperature Distribution in a Cell
- Cell-to-Cell Temperature Imbalance in a Module
- Battery Performance Prediction
- Pressure Prop and Parasitic Power
- etc.



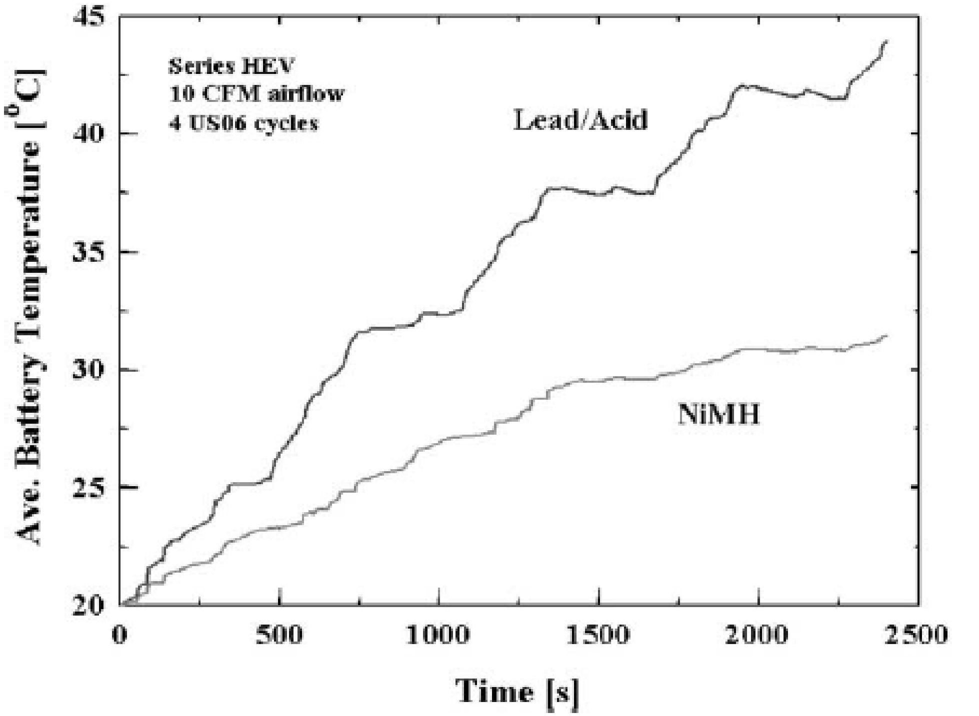
Lumped Capacitance Thermal Model for Vehicle Simulations

- **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

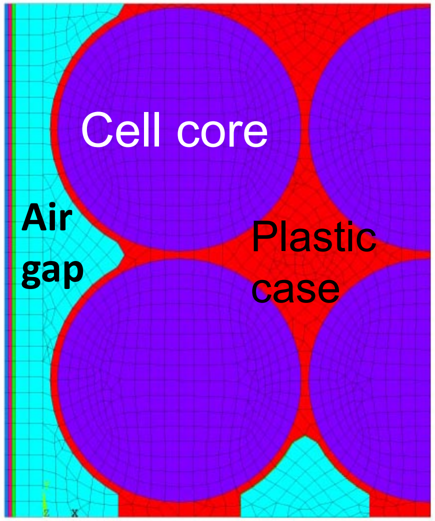


$$Q_{ess\_case} = \frac{T_{ess} - T_{air}}{R_{eff}} \qquad R_{eff} = \frac{1}{hA} + \frac{t}{kA}$$

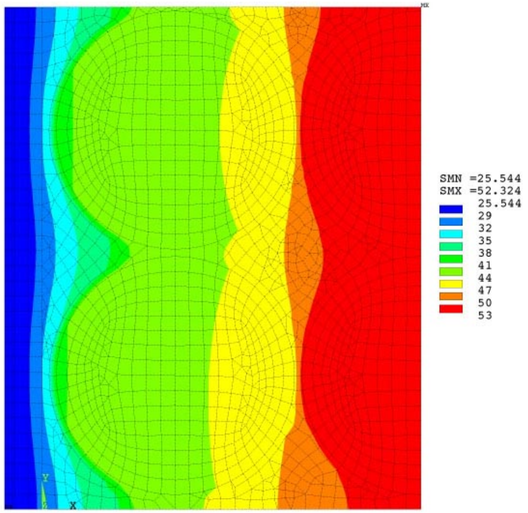
$$T_{air} = T_{amb} + \frac{0.5 Q_{ess\_case}}{\dot{m}_{air} c_{p,air}} \qquad \text{where } h = \begin{cases} h_{forced} = a\left(\dfrac{\dot{m}/\rho A}{5}\right)^{b}, & T_{ess} > \text{ess\_set\_tmp} \\ h_{natl} = 4, & T_{ess} \le \text{ess\_set\_tmp} \end{cases} \qquad T_{ess} = \int_0^t \frac{Q_{ess\_gen} - Q_{ess\_case}}{m_{ess} c_{p,ess}}\, dt$$

Example of 2-D Module Thermal Modeling

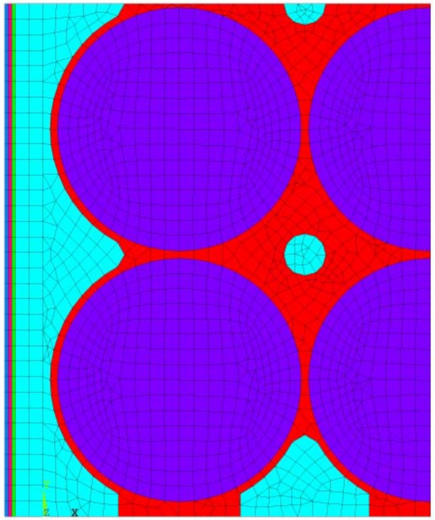
Case 1. No holes and no air flow between cells



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

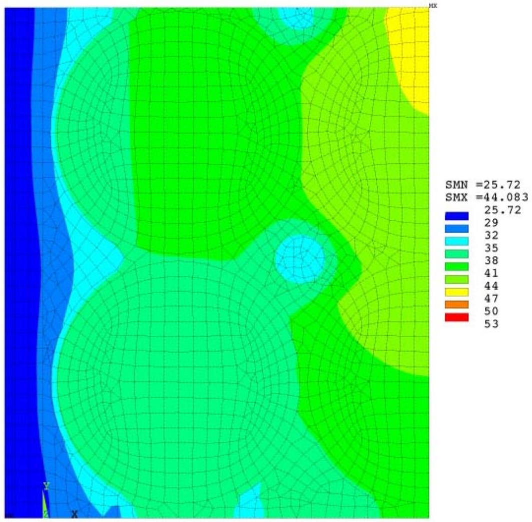
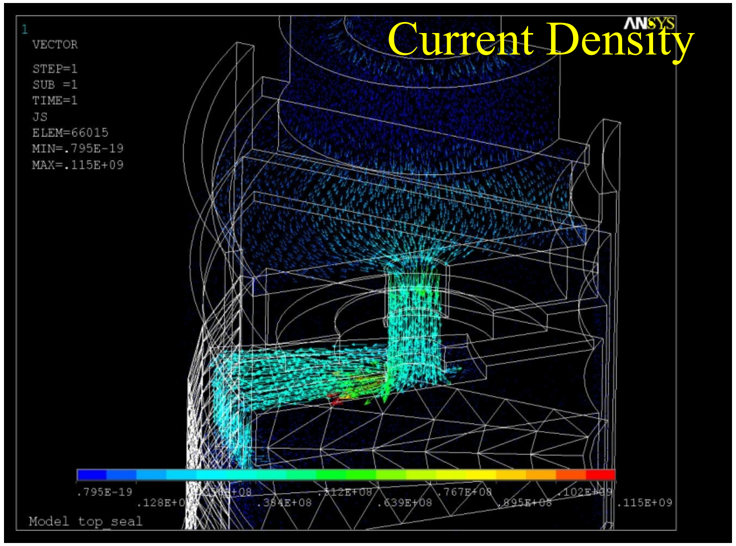
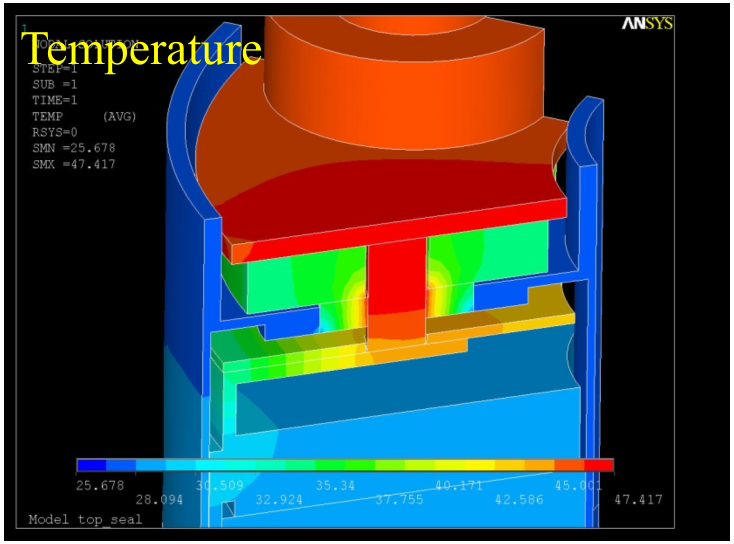


Photo Credits: David Parsons, NREL

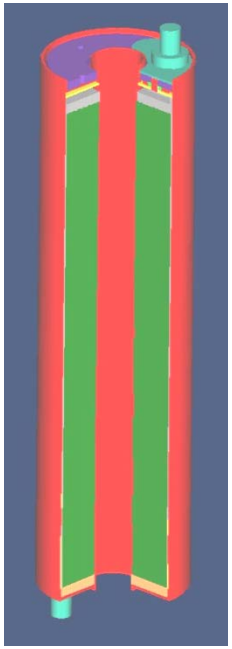
Electro-Thermal Analysis Approach

- 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



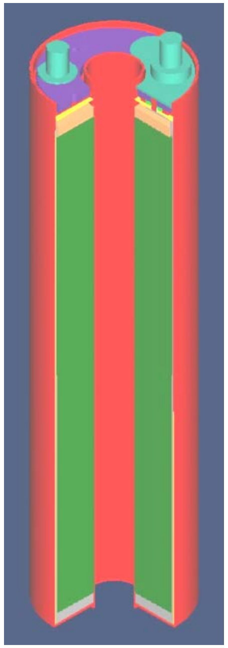


Example of 3-D Electro-Thermal Modeling



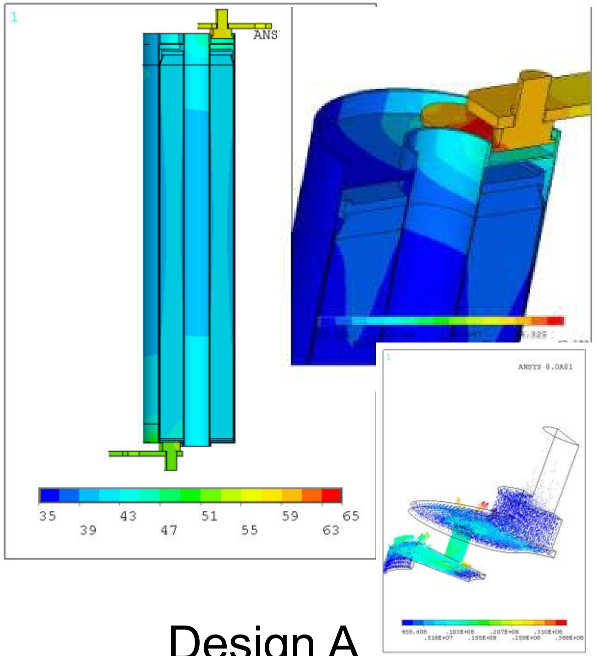
Design A
Terminals on each side

16 Ah
Power Cell

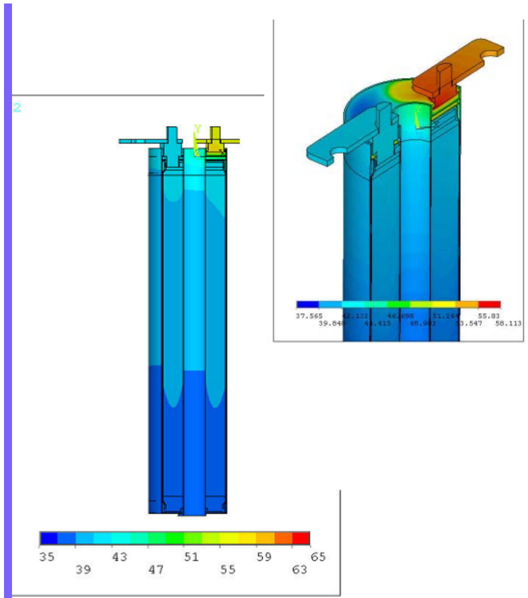


Design B
Terminals on the same side

Photo Credit: Ahmad Pesaran



Design A
Thermal Response



Design B
Thermal Response

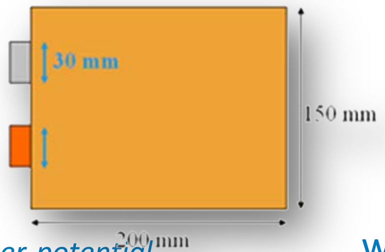
Under 110 A RMS load
Dist Design A

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

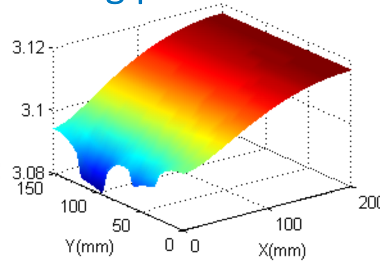


Comparison of two 40-Ah Li-ion prismatic cell designs

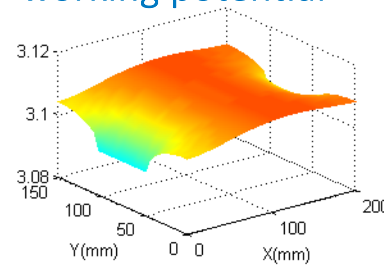
2 min 5C discharge

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

working potential

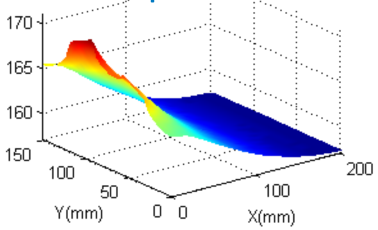


working potential

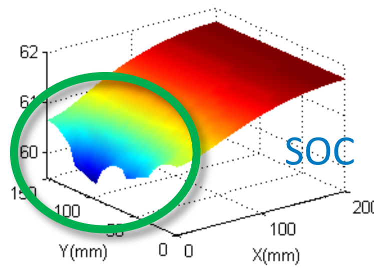


This cell is cycled more uniformly, can therefore use less active material ($) and has longer life.

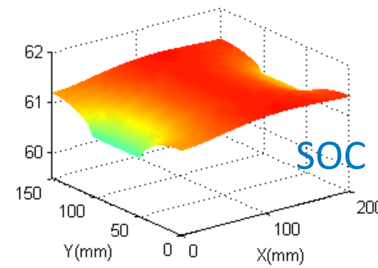
electrochemical current production



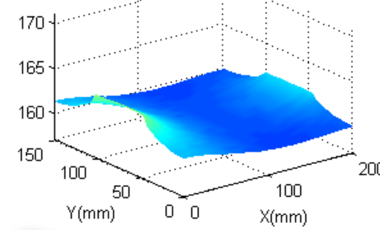
SOC



SOC

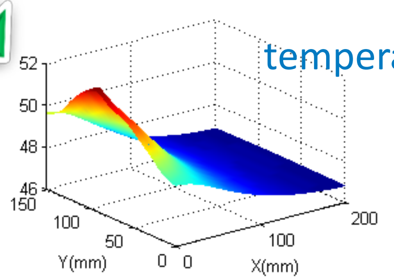


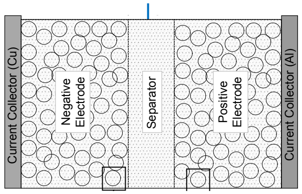
electrochemical current production



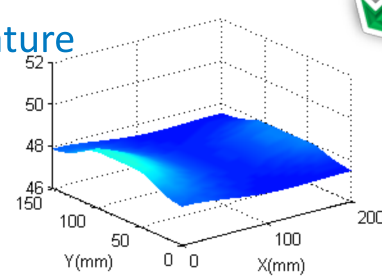
- *High temperature promotes faster electrochemical reaction*
- *Higher localized reaction causes more heat generation*

temperature



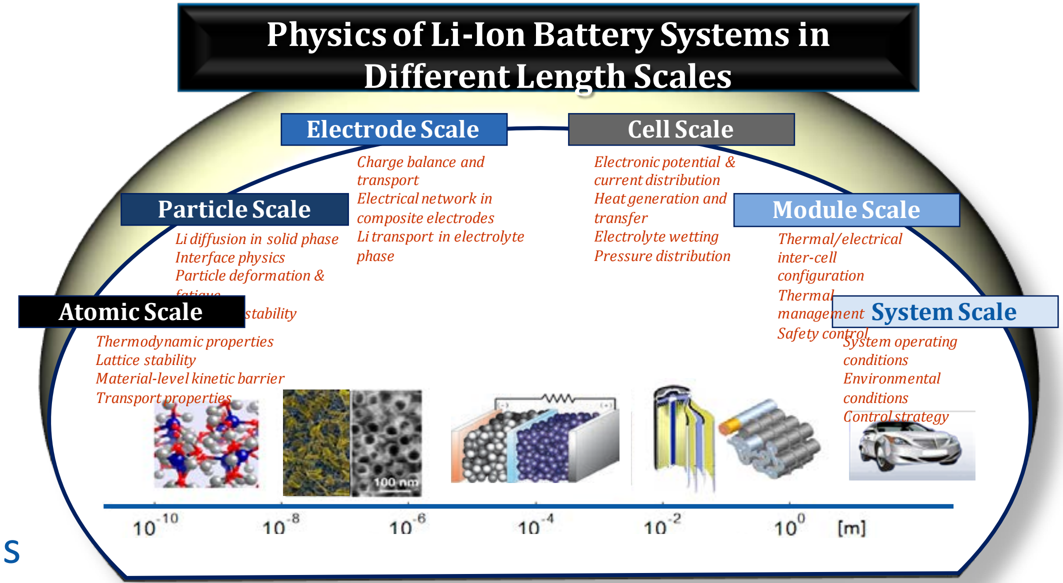


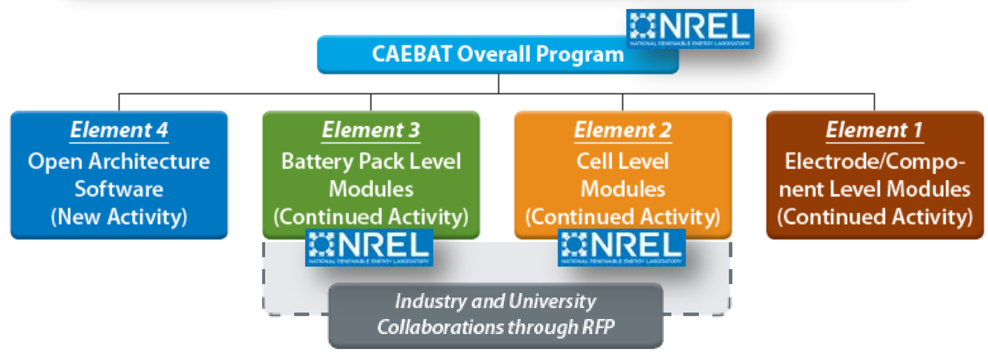
temperature

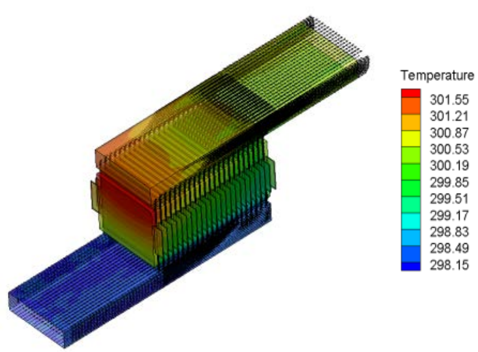


Computer-Aided Engineering of Batteries (CAEBAT)

- 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

Acknowledgments

- **Support provided by the DOE Vehicle Technologies Program**
  - Dave Howell, Hybrid and Electric Systems Team Lead
  - Brian Cunningham, Energy Storage Technology Manager
- **Feedback from CAEBAT Subcontract Technical Leads**
  - Taeyoung Han (General Motors)
  - Steve Hartridge (CD-adapco)
  - Christian Shaffer (EC Power)
- **Support from NREL Staff**
  - John Ireland
  - Dirk Long
  - Mark Mihalic
  - Marissa Rusinek

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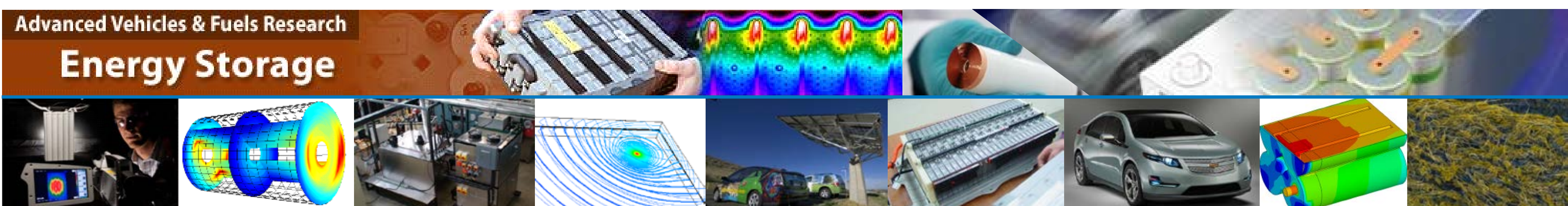

nrel.gov/vehiclesandfuels/energystorage