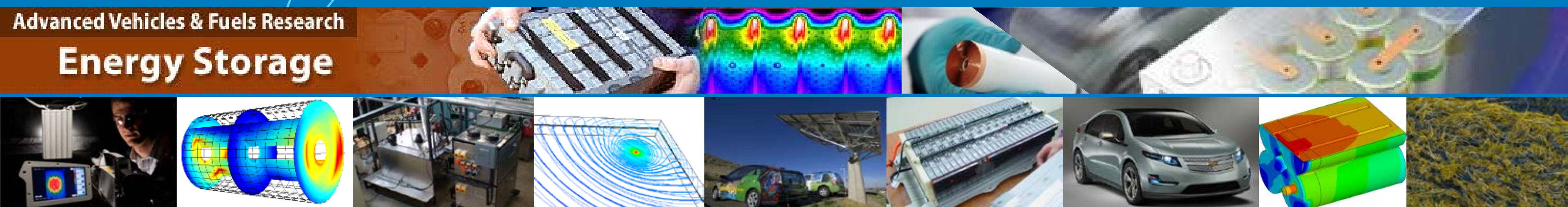
# Battery Pack Thermal Design



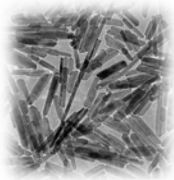
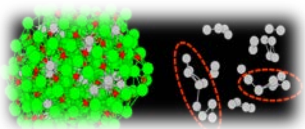

**Ahmad Pesaran**

National Renewable Energy Laboratory
Golden, Colorado

**NREL/PR-5400-66960**

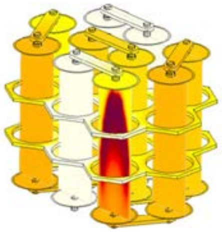
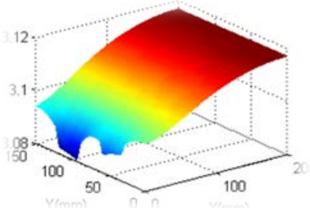
# NREL Energy Storage R&D

Collaborating with industry to achieve energy storage targets for different applications

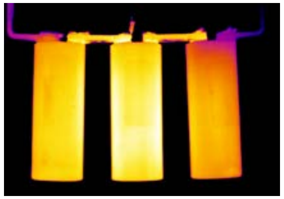
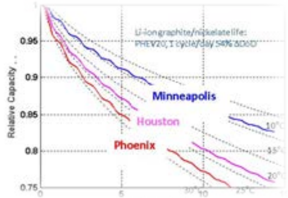



**Materials Synthesis and Processing**
**(Improve energy density and stability)**


**Component Testing and Characterization**
**(Evaluate performance, life, and safety)**

**Multi-physics Battery Modeling**
**(Improve performance, life, and safety)**

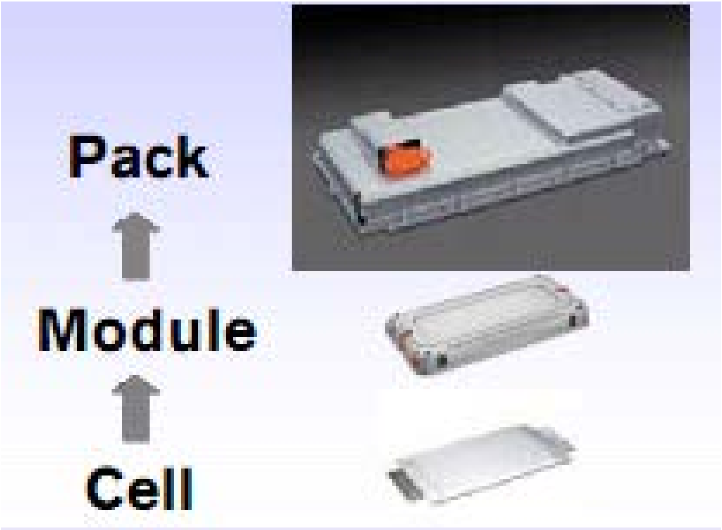

**Diagnostic, Management, and Control**
**(Enhance life utilization)**

**System Evaluation and Techno-Economics**
**(Find cost-effective pathways)**

# Battery Pack Design

## Selecting a high-performing design is just a start

- **Series and parallel integration of cells to achieve required**
  - Required energy and power
  - Max and min voltage
  - Calendar and cycle life
  - Cost targets
- **Pack must be safe**
  - Mechanical/structural
  - Electrical
  - Thermal
- **Management and Control**
  - Mechanical management – Robust packaging for shock, vibration, crush
  - Thermal management – Life, performance, safety
  - Electrical management – Balancing, performance , life,  safety
- **Other**
  - Manufacturability
  - Recyclability
  - Diagnostics
  - Maintenance/repair



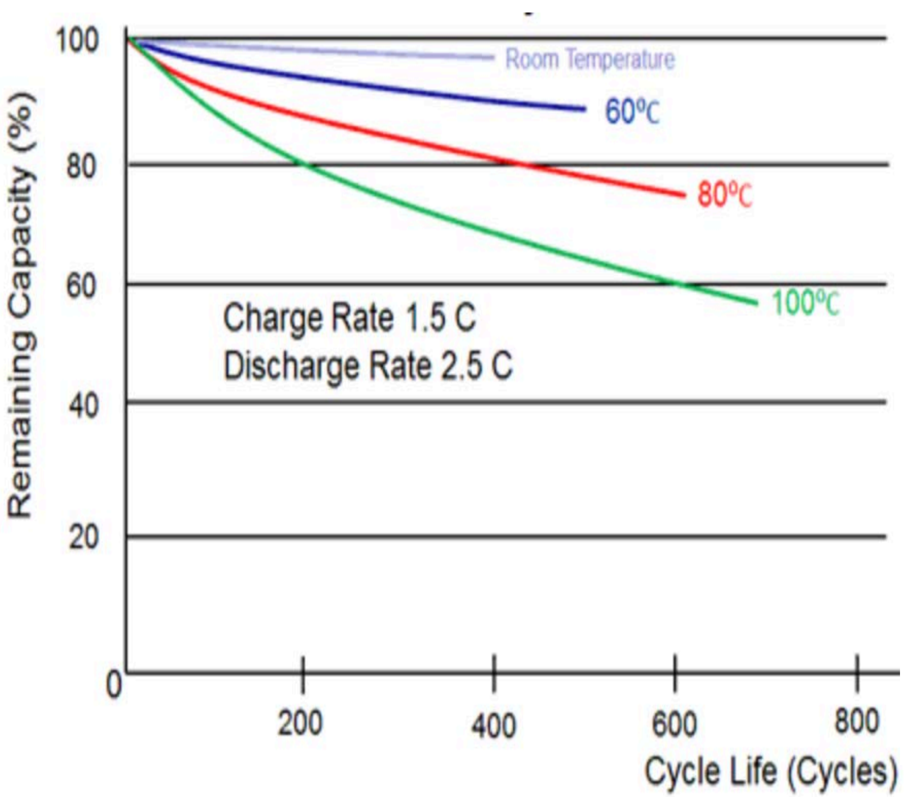
# Battery Thermal Design

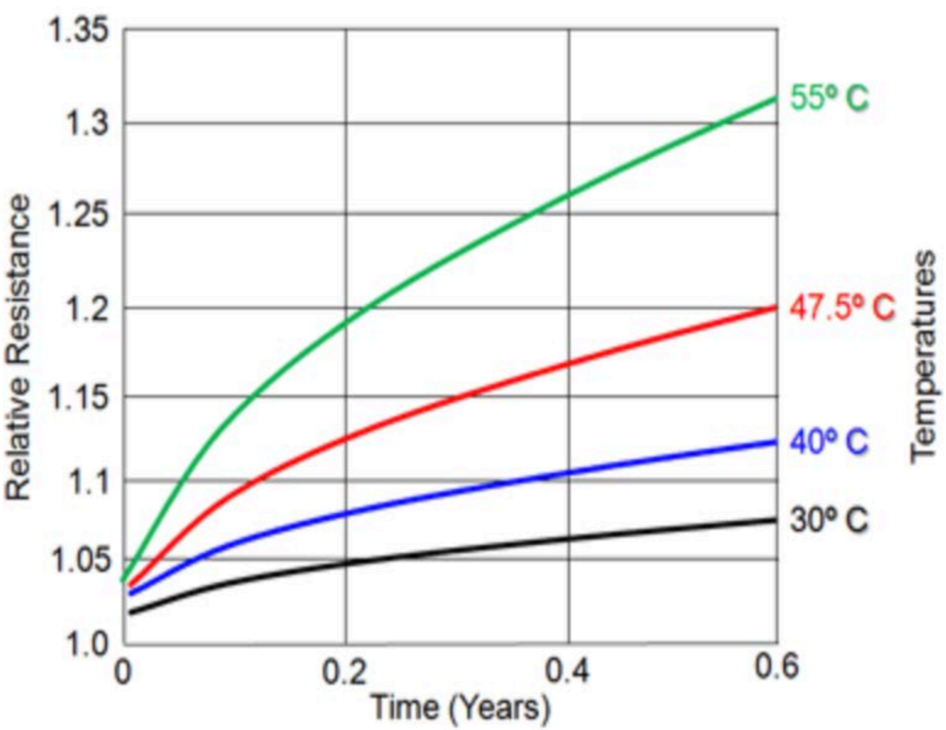
- **Normal Operation**
  - Normal driving
  - Every day

- **Off-Normal Operation**
  - Abuse conditions
  - Rare

# Temperature Impact on LIB

- Lithium-ion batteries (LIB) are the technology of choice for many applications
- LIBs are sensitive to temperature as it impacts life, performance (capacity and resistance), safety, and (eventually) cost

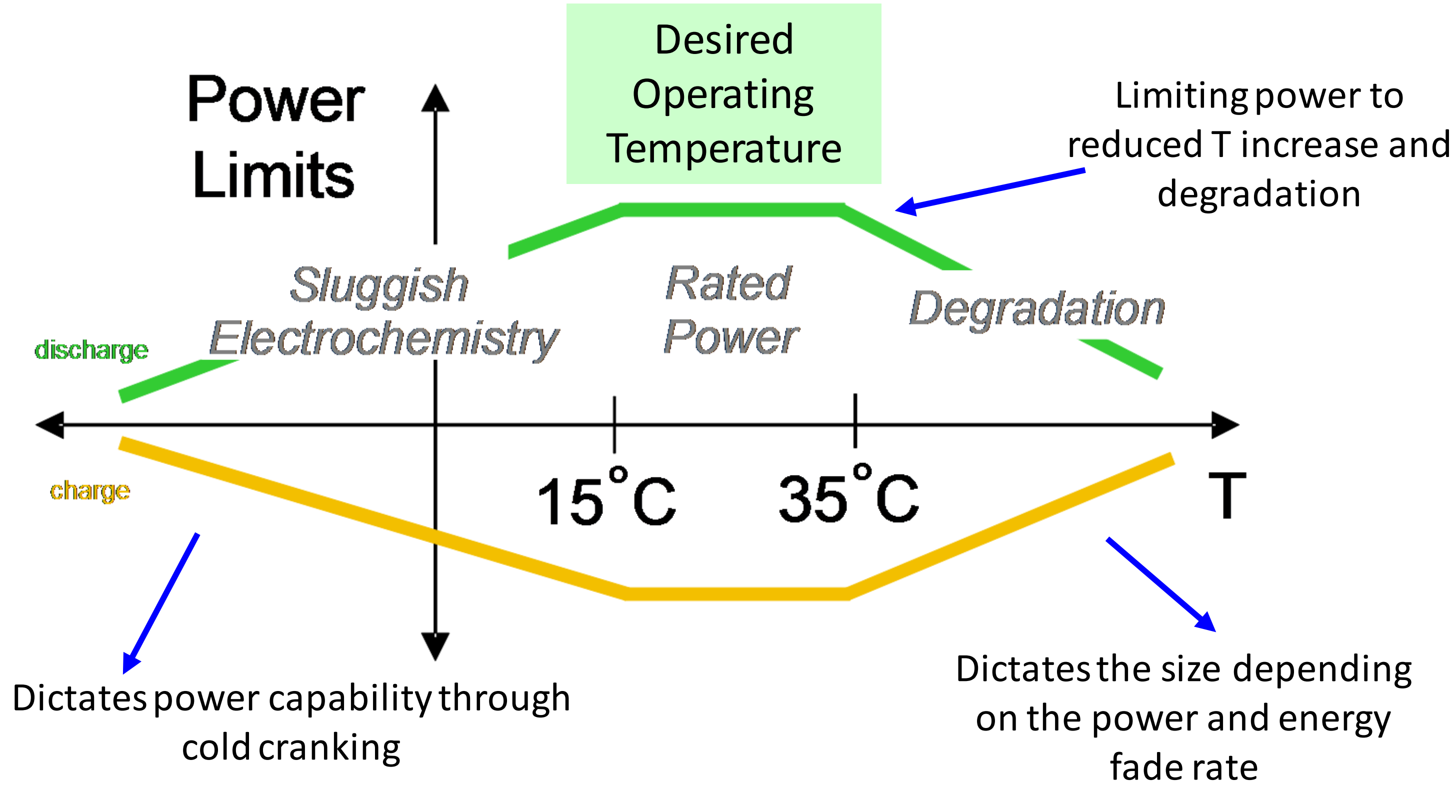



http://www.mpoweruk.com/life.htm

# Temperature Impact on xEVs

- **Higher temperatures degrade LIBs more quickly**
- **Low temperatures reduce power and energy capabilities**
- **Proper temperature control improves reliability, safety, and range**




Also limits the electric driving range

Kandler Smith, NREL Milestone Report, 2008

# xEV Thermal Management – Normal Operation

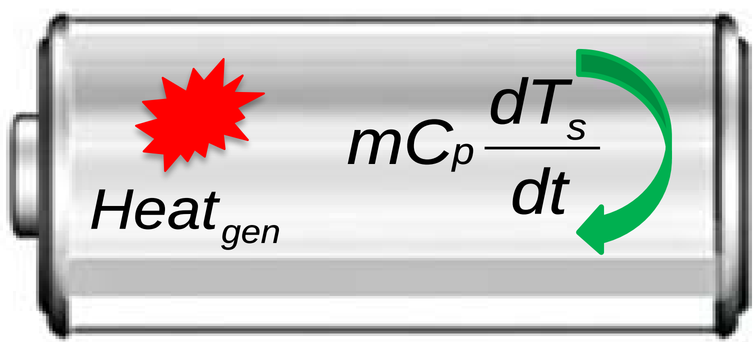
- **Battery thermal management is needed for xEVs to:**
  - Keep the cells in the desired temperature range
  - Minimize cell-to-cell temperature variations
  - Prevent the battery from going above or below acceptable limits
  - Maximize useful energy from cells and pack
- **However, a battery thermal management systems (BTMS) should be designed to:**
  - Minimize increased complexity
  - Added initial cost provide long term value
  - Improve reliability
  - Minimize parasitic losses

# Battery Heat Balance – Lumped Capacitance

**Assuming battery is isothermal (has 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 Loss** | **Radiation Heat Loss** | **Conduction Heat Loss**




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

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

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

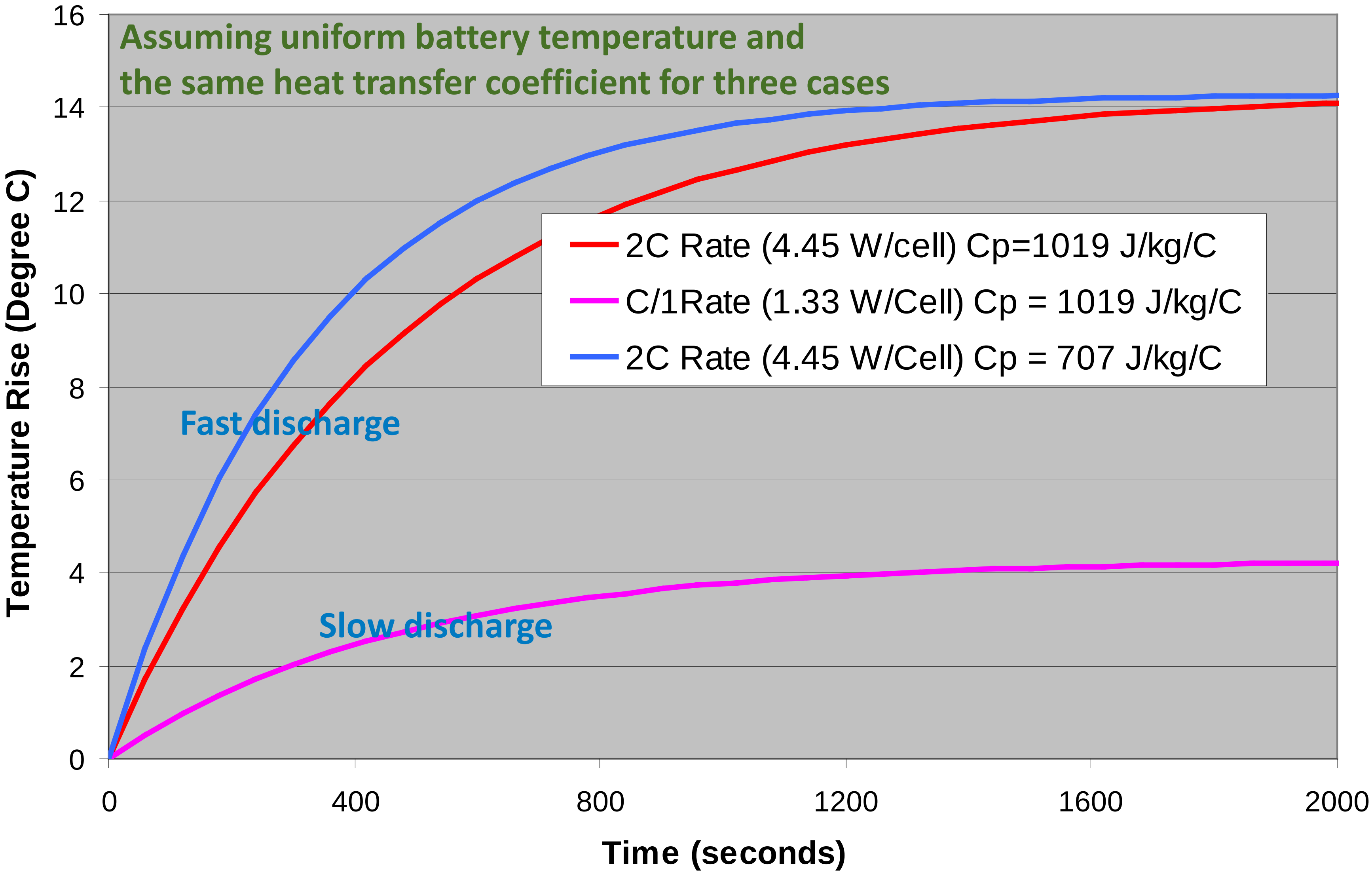
D. Bernardi, E. Pawlikowski and J. Newman

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

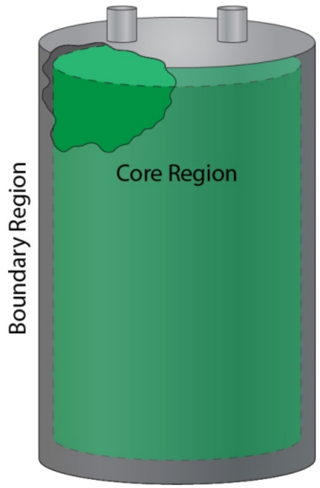
$T_s$ = Battery Temp

$T_a$ = Ambient Temp

# Heat Generation Rate and Specific Heat Impact Battery Temperature Rise



# Battery Heat Transfer – none isothermal

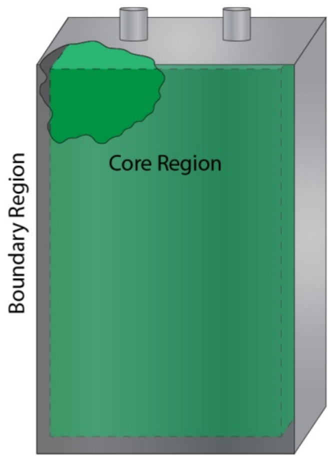



**Could be 2 or 3 dimensional in geometry**

**Core region**

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

$k : thermal\ conductivity$




**Case or boundary region**

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

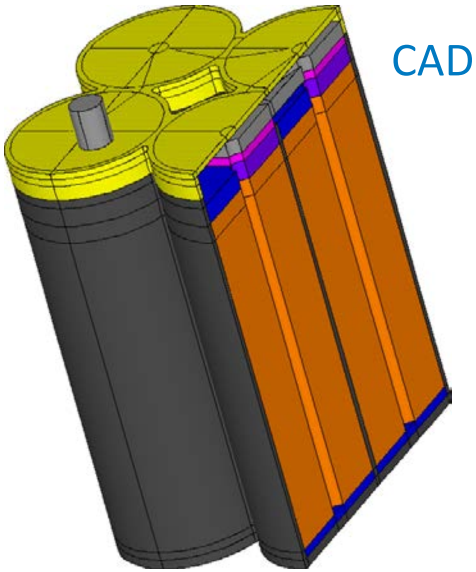
| Heat flux from the core | Convection from various case surfaces | Radiation from various case surfaces | Heat accumulation in the case |
|---|---|---|---|

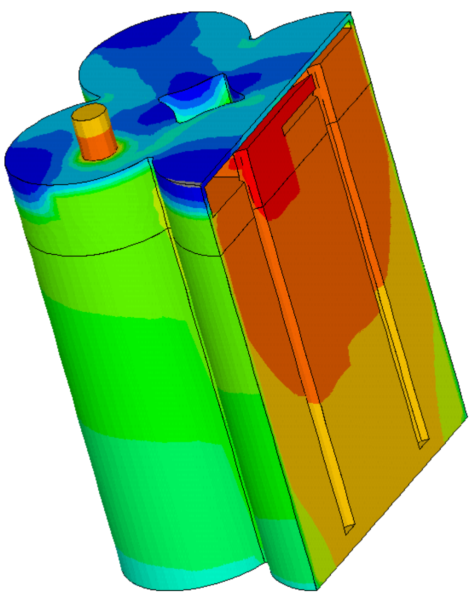
Johnsee Lee, K. W. Choi, N. P. Yao and C. C. Christianson

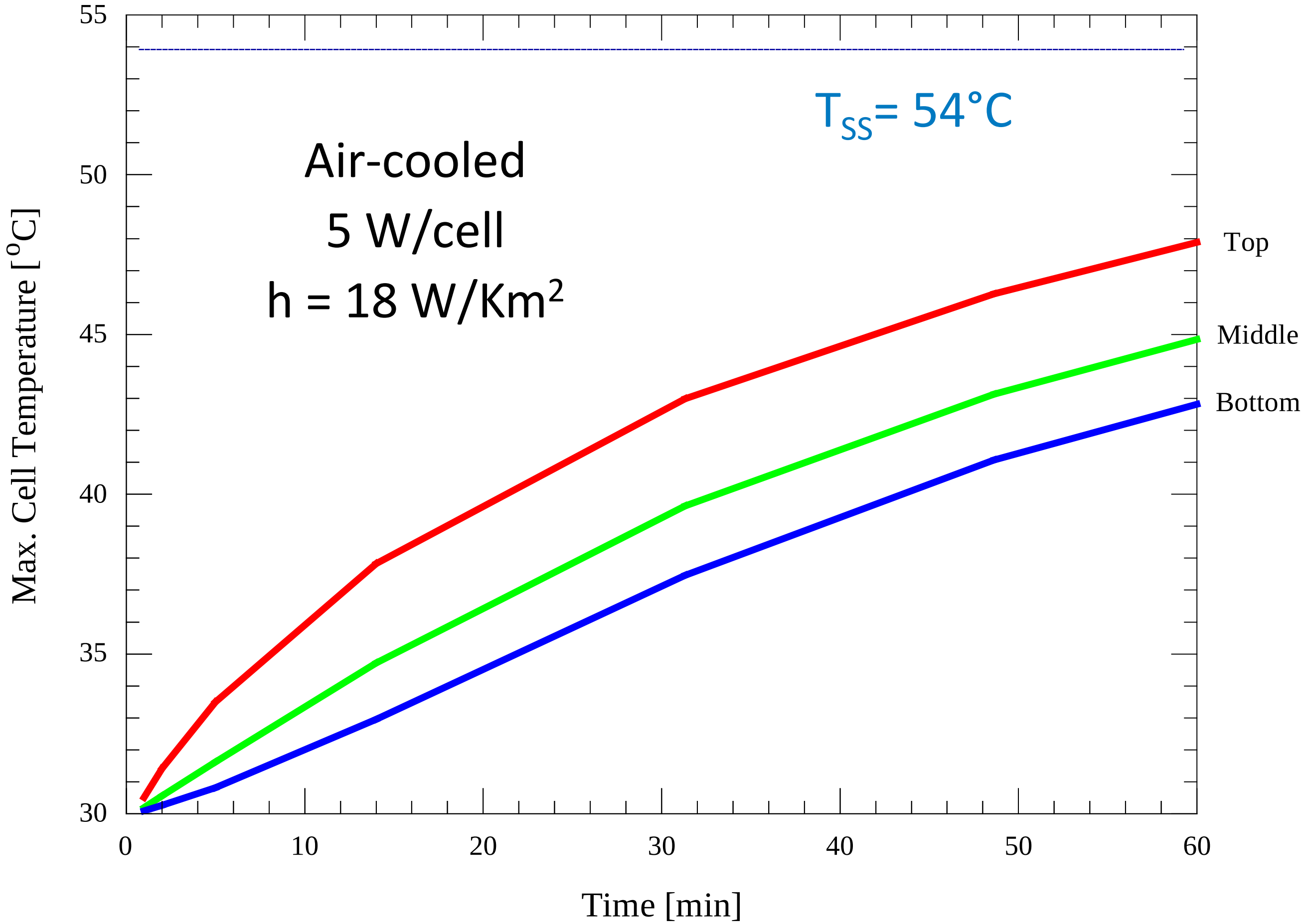
*J. Electrochem. Soc.* 1986, Volume 133, Issue 7, Pages 1286-1291

# Example of T Distribution in a 6-cell Module

CAD of a 6-cell module





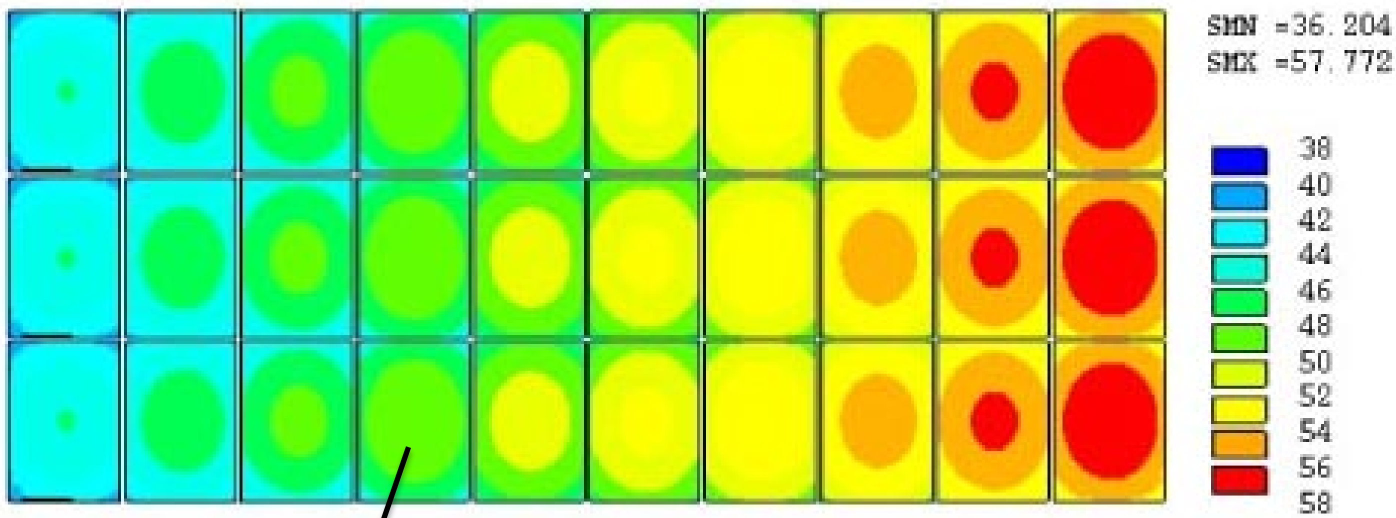



A. Pesaran, A. Vlahinos, S. Burch. Proceedings of the 14th Electric Vehicle Symposium, December 1997

# Heat Transfer in a Battery Pack

Coolant Flow Rate ($M_c$) for each cells in series

$T_{in}$ $T_{out}$




$Q_{Gen}$

(Heat Generation within a cell)

$$M_c \; C_p (T_{out} - T_{in}) = \Sigma \, Q_{Gen}$$

# Information Needed for BTMS Design

- ***Acceptable temperature range***
- ***Acceptable temperature difference***
- ***Maximum and minimum temperature limits***
- **Thermo-physical properties**
- **Battery heat generation rates**
- **Heat rejection rates from battery**
- **Configurations and dimensions of cells and proposed BTMS**
- **Parasitic power needed to push fluids/cooling through BTMS**

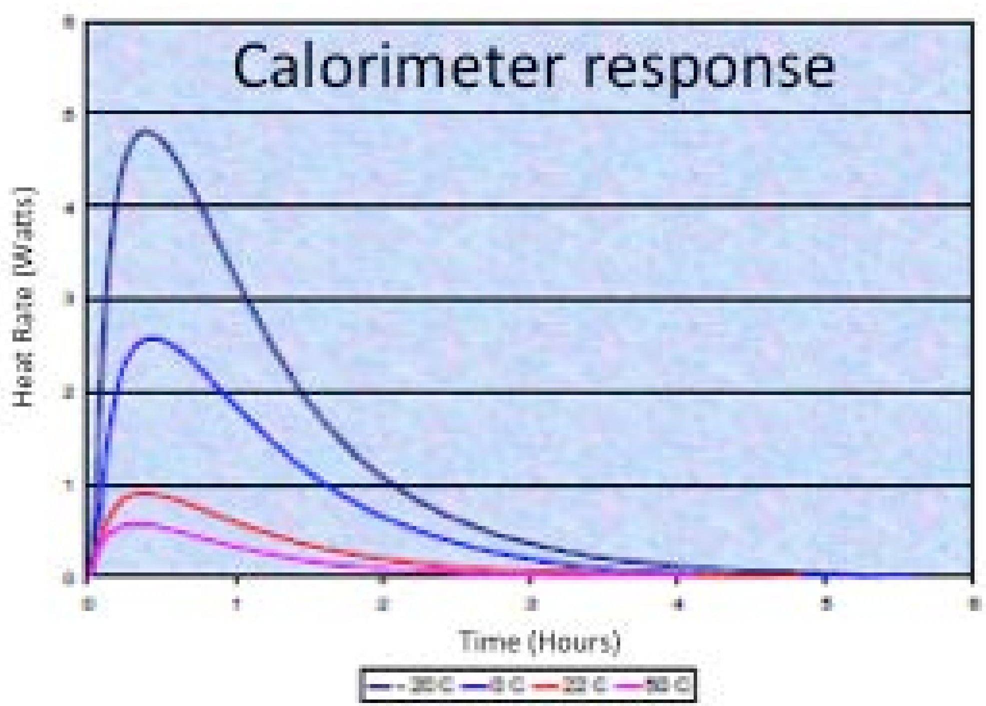
# Tools for Designing BTMS

- **Experimental Tools**
  - Isothermal calorimeters and battery testers
  - Infrared thermal imaging
  - Thermal conductivity meters
  - Set up to measure heat transfer characteristics
  - Battery thermal testing loop

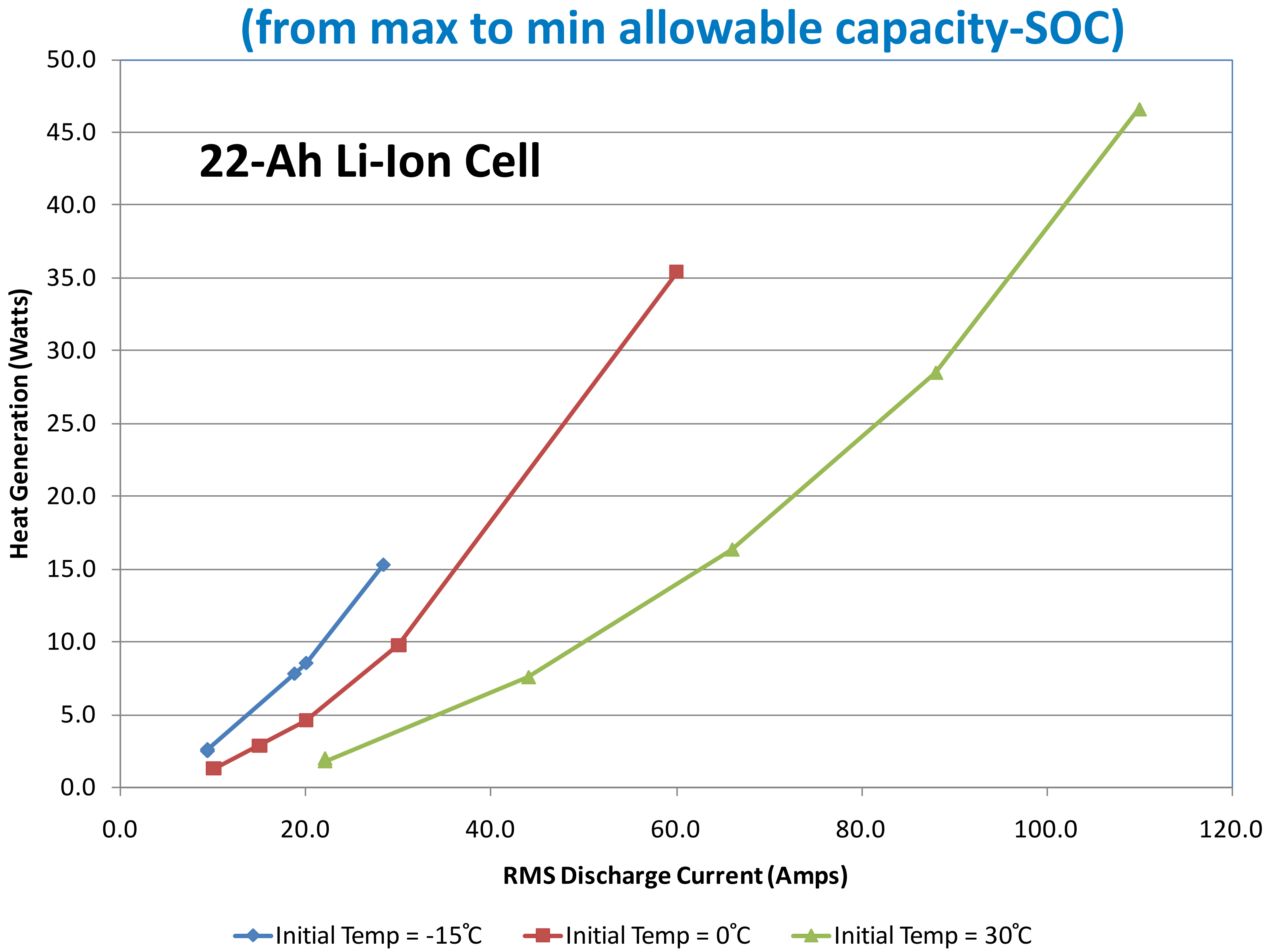
- **Modeling Tools**
  - First-order/lumped capacitance thermal and fluid models
  - 1-D, 2-D, 3-D thermal and fluid-flow performance models
  - 3-D electrochemical-thermal model
  - Computer-aided engineering software with CFD

# Measuring Heat Generation

- Isothermal conduction calorimeters along with battery testers are best equipment  to measure **heat generation** at various current rates, temperatures, and states of charge (SOCs)
- Heat flux gauges measure heat exchanges from a battery and between a constant temperature heat sink

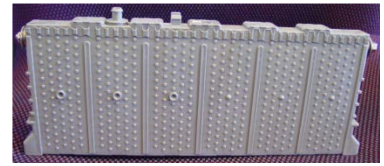


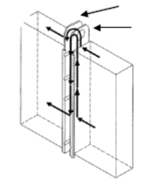
# Example Heat Generation Data for CC Discharge

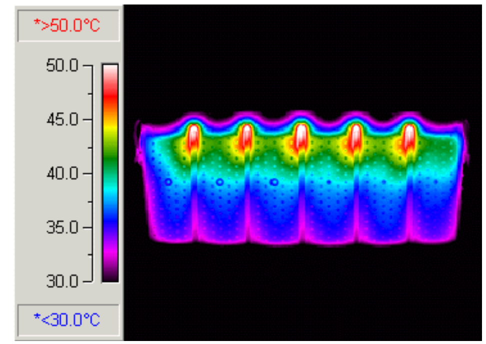


# Infrared Battery Thermal Imaging

- **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








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

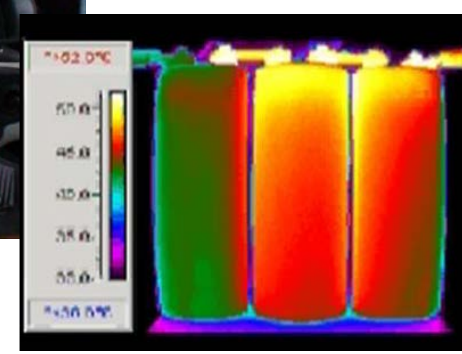
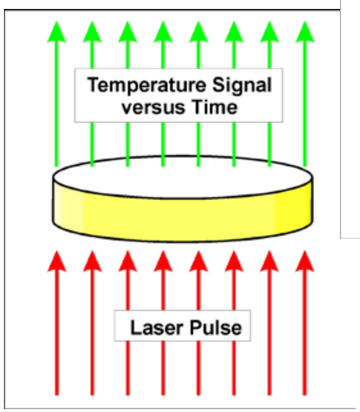
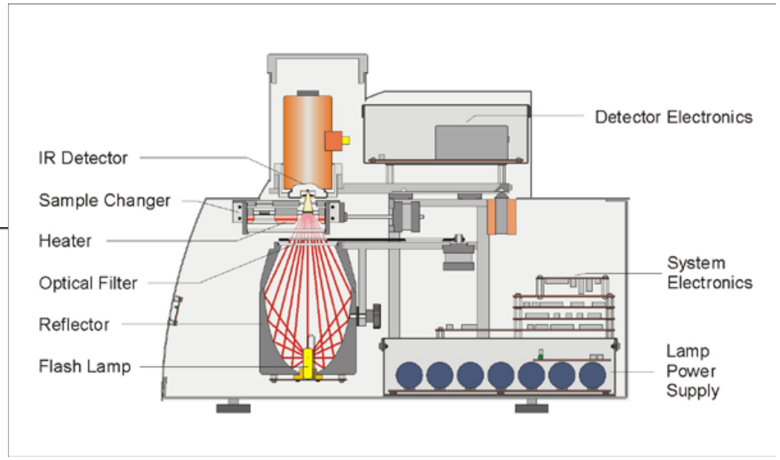


Photo Credits: Matt Keyser, NREL

# Measuring Thermal Conductivity of LIB Components

## Flash Diffusivity Method:




Provided by Peter Ralbovsky, Netzsch Instruments

Netzsch LFA 447 Unit

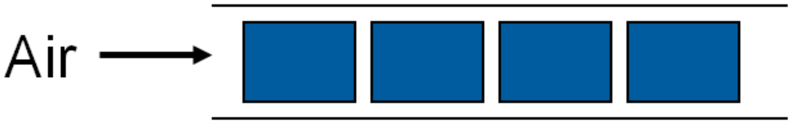
- **Measurements have shown that generally the thermal conductivity of a LIB is much lower in-plane than cross-plane**

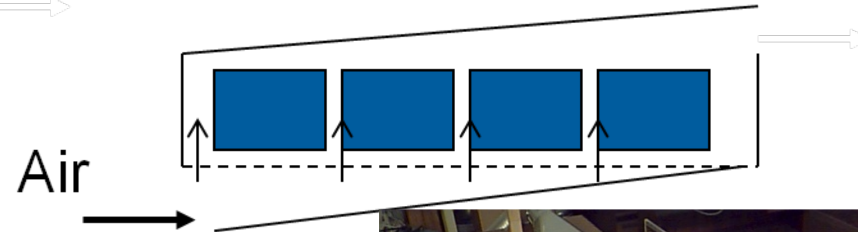
**In plane ~ 0.8 to 1.1 W/m/K    Cross plane ~ 28 to 35 W/m/K**

Photo Credit: John Ireland, NREL

# Battery Thermal Testing Loops

- **Measuring heat transfer coefficients or conductance**



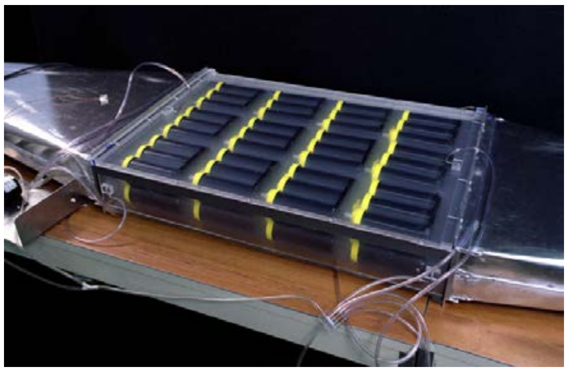
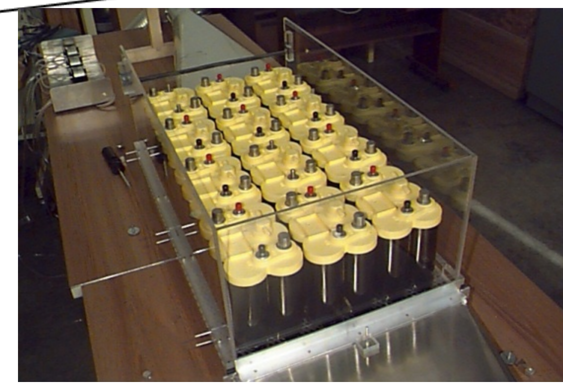



Photo Credits: Ahmad Pesaran



- **Hardware in the loop thermal testing**

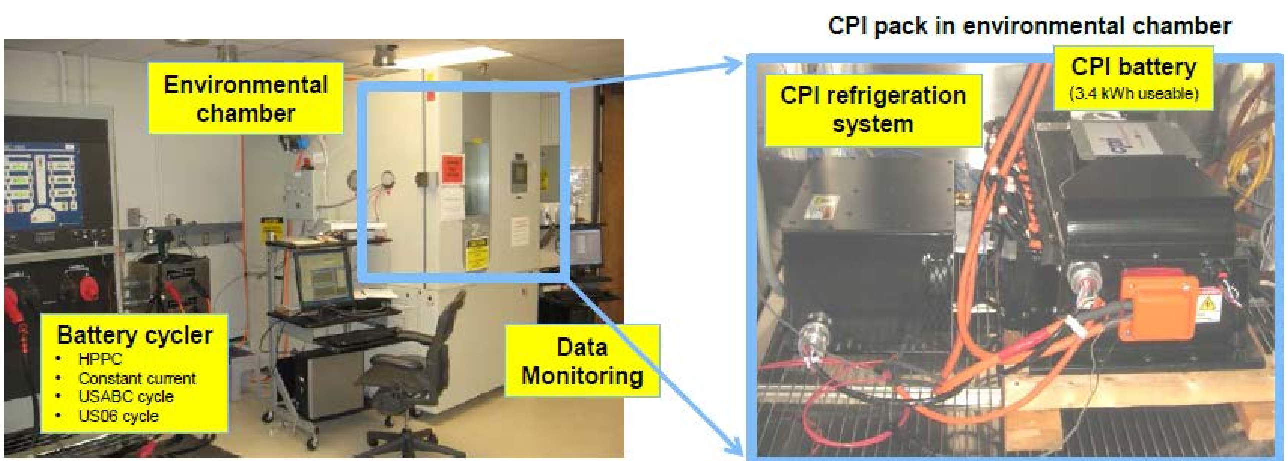
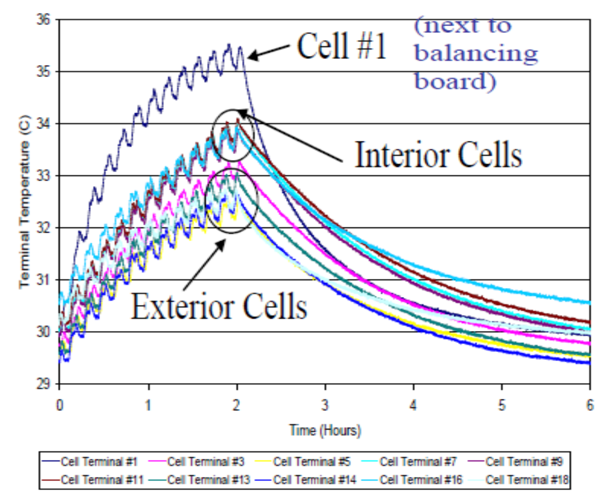
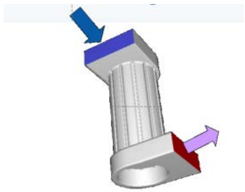



Photo Credits: Kandler Smith, NREL




Temp dist. in a USABC module

# Process for Battery Thermal Design

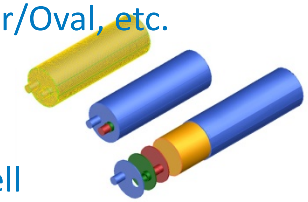


## Module Cooling Strategy

- 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.

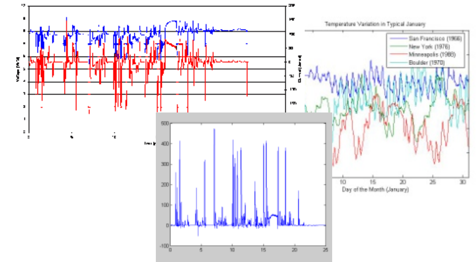
## Cell Characteristics

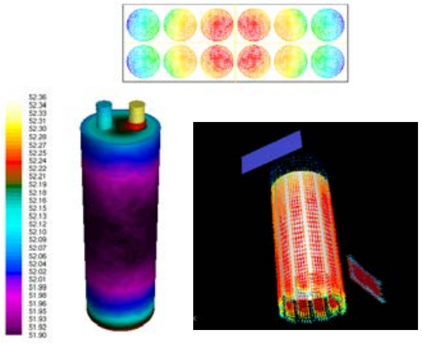
- Shape and size : Prismatic/Cylinder/Oval, etc.
- Materials/Chemistries
- Voltage/current & heat gen data
- Thermal/Current Paths inside a Cell




## Operating Conditions

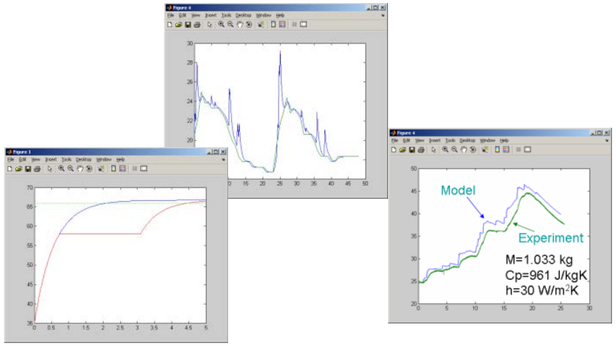
- Vehicle Driving Cycles
- Control Strategy
- Ambient Temperature
- etc.





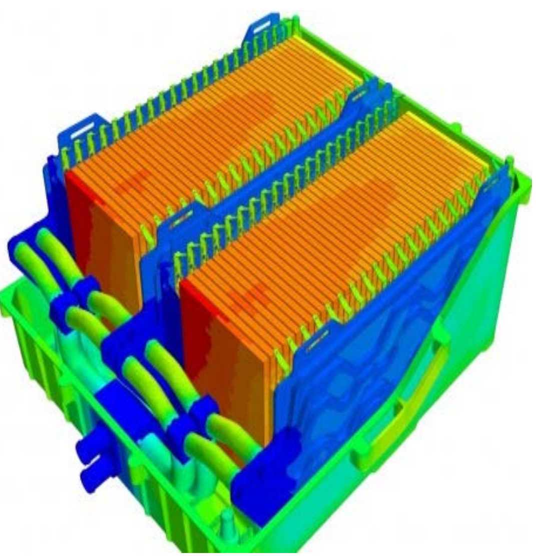
## Battery Thermal Responses

- 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.

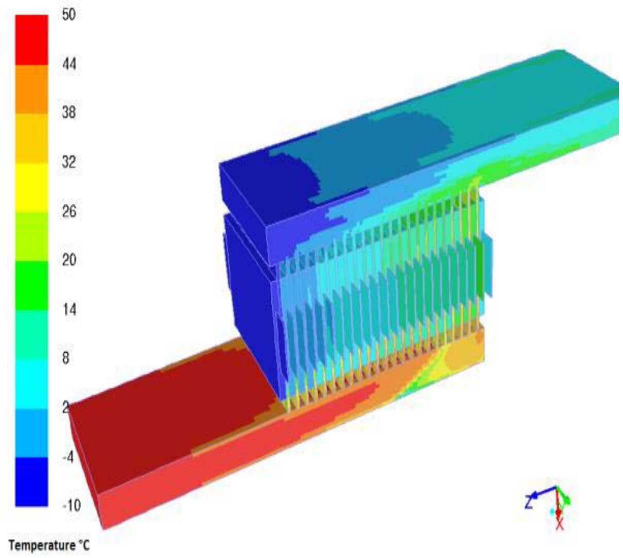


# Computer Aided Engineering of Batteries

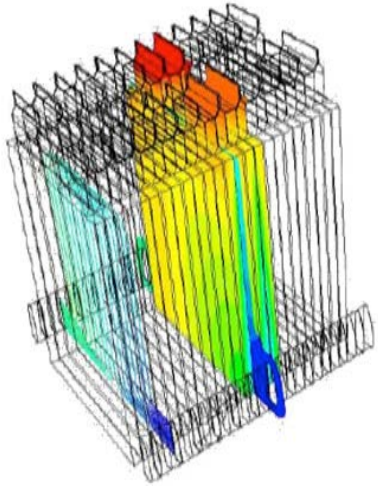
- Combines fluid flow, thermal, and electrochemical models in one package



CD-adapco




EC Power



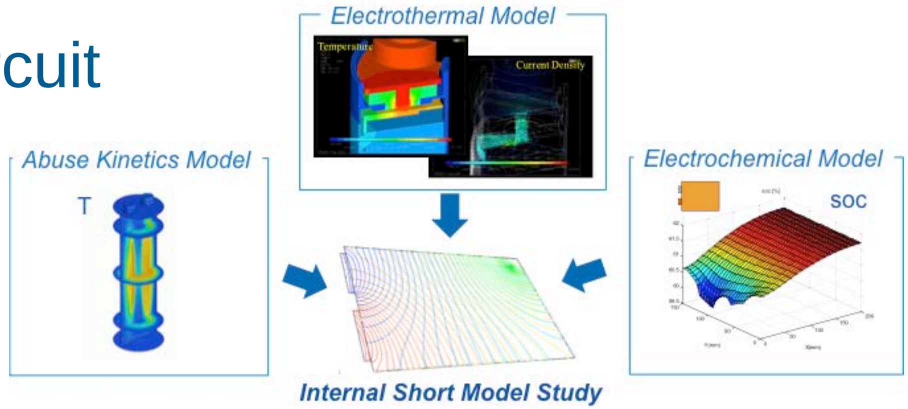
ANSYS

# Battery Thermal Design

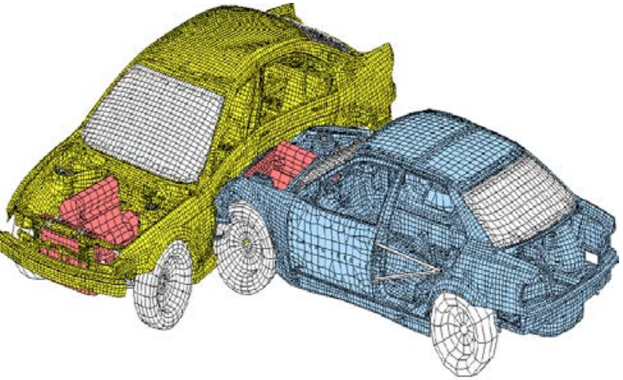
- **Normal Operation**
  - Normal driving
- **Off-Normal Operation**
  - Abuse conditions

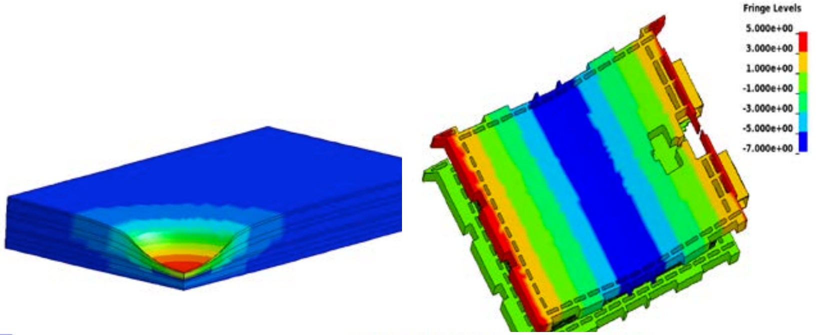
# Off-Normal Operation – Examples

- Internal and external short circuit

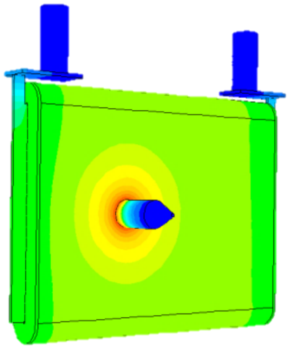



- Overheating
- Crash induced crush

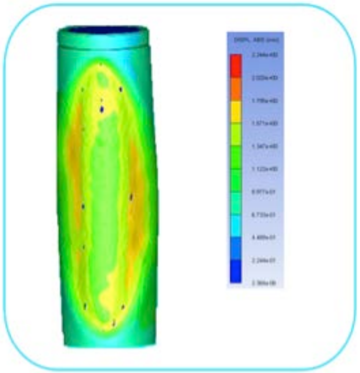





- Sharp object penetration



Deformation due to Pressure-Distribution within an 18650 cell



- Overcharge

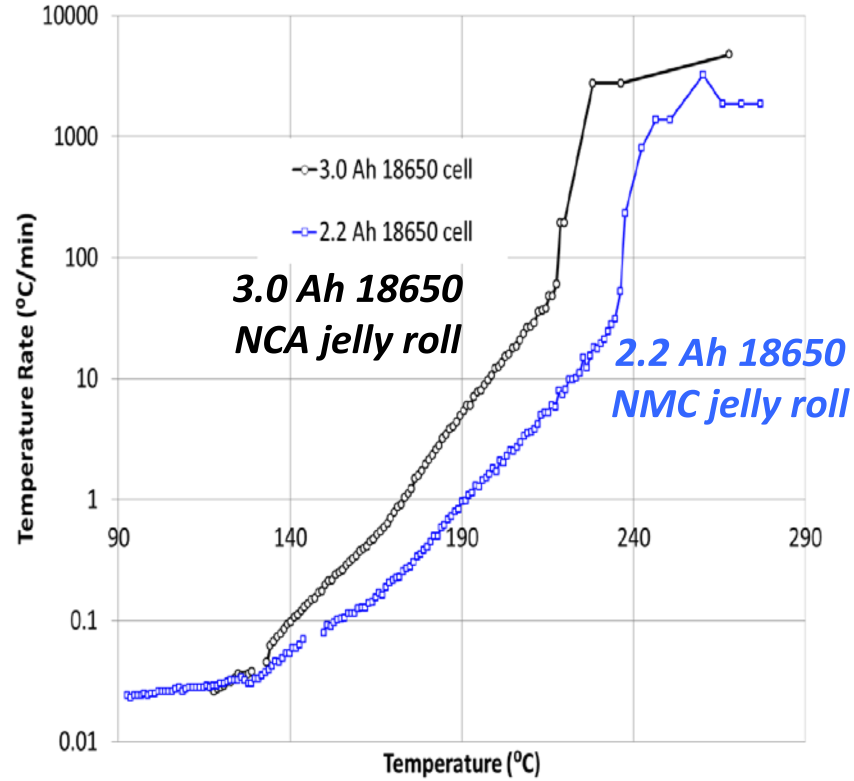
# Accelerating Rate Calorimeter Testing

## Measuring Heat during Thermal Runaway (TR)


**NREL's THT EV Accelerating Rate Calorimeter**



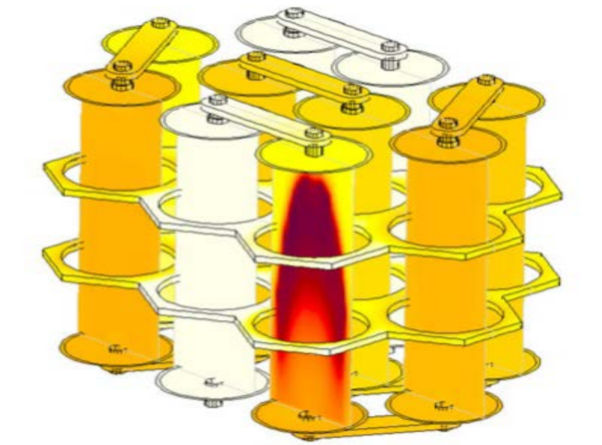
***3 Ah jelly roll rapid thermal runaway (>10°C /min) occurs 20°C lower than 2.2 Ah cell***

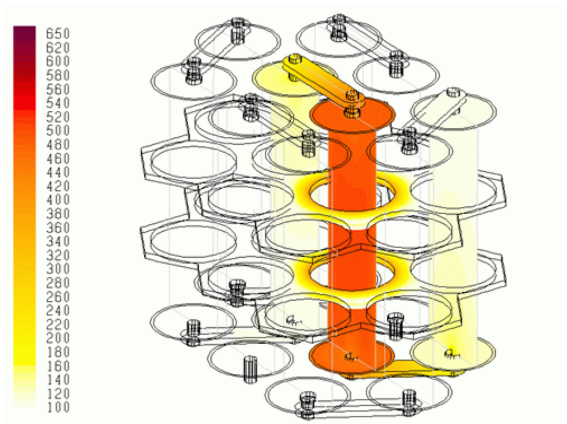



| Jelly Roll | Weight (g) | Onset Temp (°C) | Peak Temp(°C) | Venting Temp(°C) | Total Heat Generation (J) | Runaway Enthalpy(kJ/Ah) | Mass Change (g) |
|---|---|---|---|---|---|---|---|
| 18650 3.0 Ah | 45.23 | 111.6 | 932.4 | 128.0 | 31,002.91 | 10.33 | 13.27 (29.3%) |
| 18650 2.2 Ah | 43.34 | 91.5 | 782.7 | 143.7 | 25,016.76 | 11.37 | 8.97 (20.1%) |

# Cell to Cell Thermal Propagation

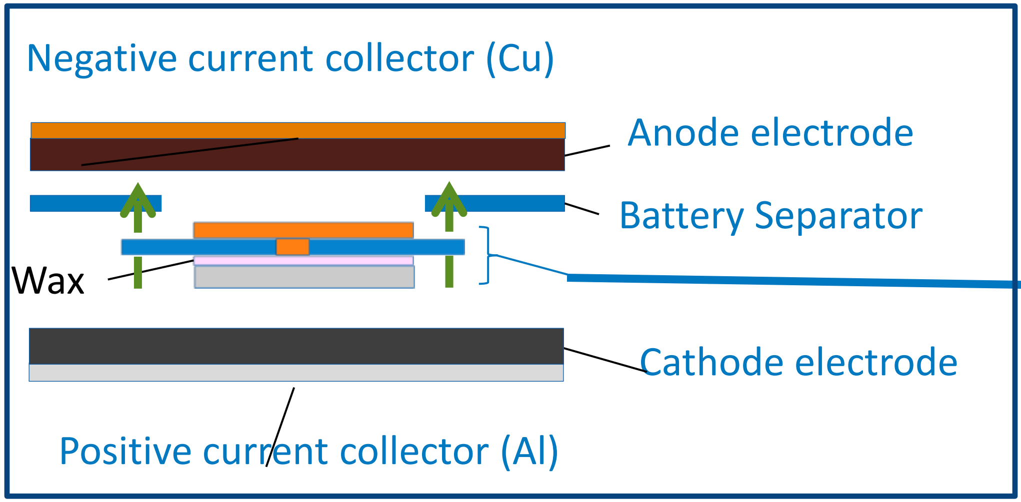
- Assuming one cell will fail and go to thermal runaway
- Is the design robust to not allow cell to cell propagation?
- How best to test the design?



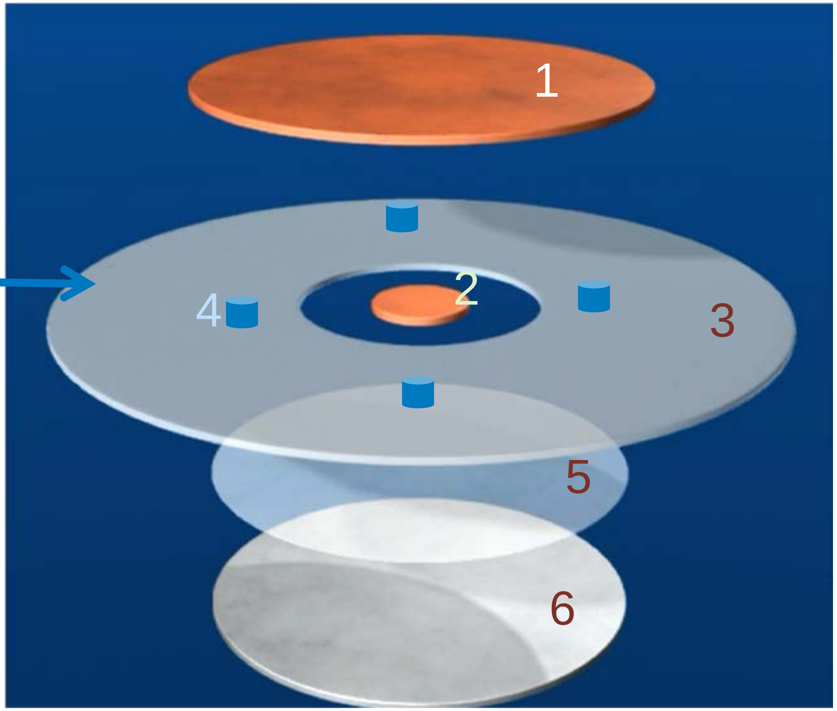



- Cell-Cell Propagation Testing using NREL Battery Internal Short Circuit (ISC) Device

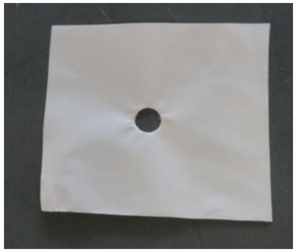
# NREL Battery ISC Device Design

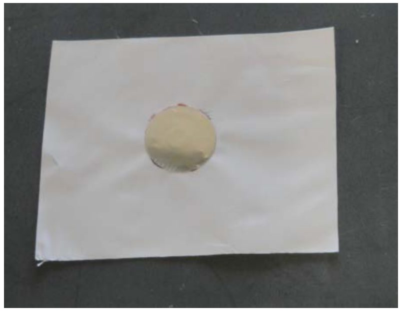



Graphics are not to scale
and for illustration only







Top to Bottom:

1. Copper Disc
2. Copper Puck
3. Battery Separator
4. Adhesive/glue
5. Phase Change Material (wax)
6. Aluminum Disc

# Evaluation of a Novel Li-ion Packaging Technology

- **Cadenza's large prismatic cell technology for grid storage and PEV**
  - Uses commoditized 26mm jelly rolls – "abundant supply chain "
  - Proprietary housing material with thermal quenching ability developed by Morgan Advanced Materials
  - Large "cells" ranging from 30Ah to 200Ah in development
  - Expected low cost $125/kWh
  - Feature: Ability to survive internal short without cascading allows high energy density

110 Ah demo "cell"

- **Department of Energy/ARPA-E Range Team**
  - Cadenza Innovation LLC (Principal), Fiat Chrysler Automobiles, NREL, Samsung SDI NA, Morgan Advanced Materials, Magna Styer Battery Systems, Alcoa, Karotech LLC, and Impact Design LLC

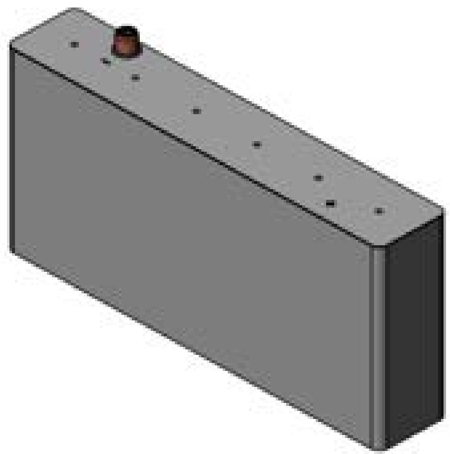
# Cell to Cell Propagation Study Using ISC Device

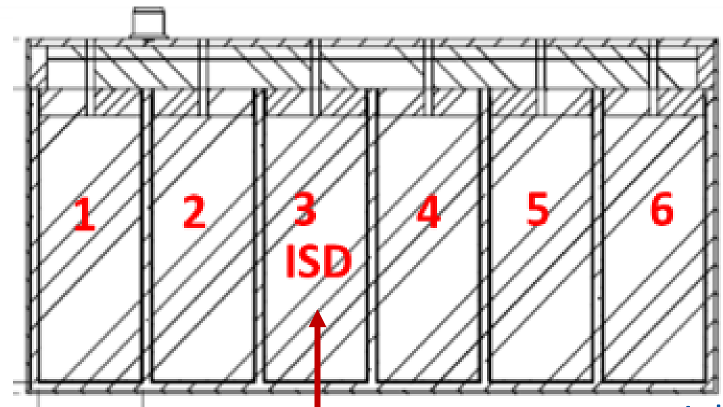
- **Intended application for ARPA-E project**
  - Fiat 500e (24kWh original battery)
  - DEMO battery project: 38kWh (in the same volume)
- **Proof-of-concept cells to date for two systems:**
  - 6 jellyrolls in a row: 30Ah (NCM)
  - 23 jellyrolls in an array: 90Ah (NCA)

# ISC Device in a 30Ah NCM cell and a 90 Ah NCA

One cell with internal short circuit device implanted jelly rolls

30Ah “cell” consisting of 6 x 5Ah NCM jelly rolls

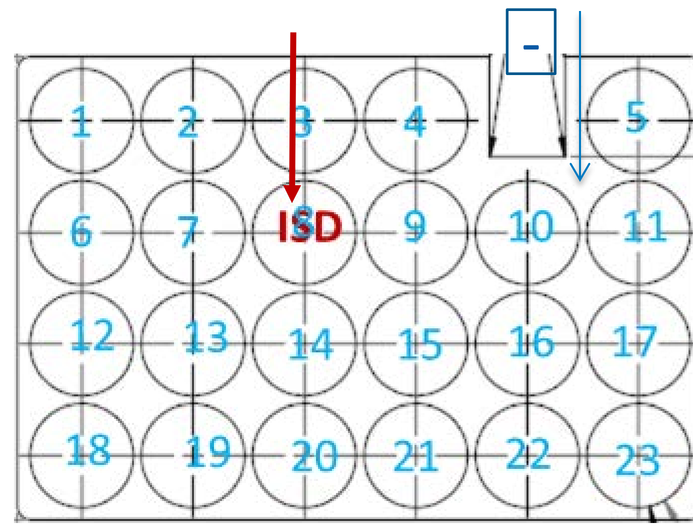





ISD implanted jelly roll

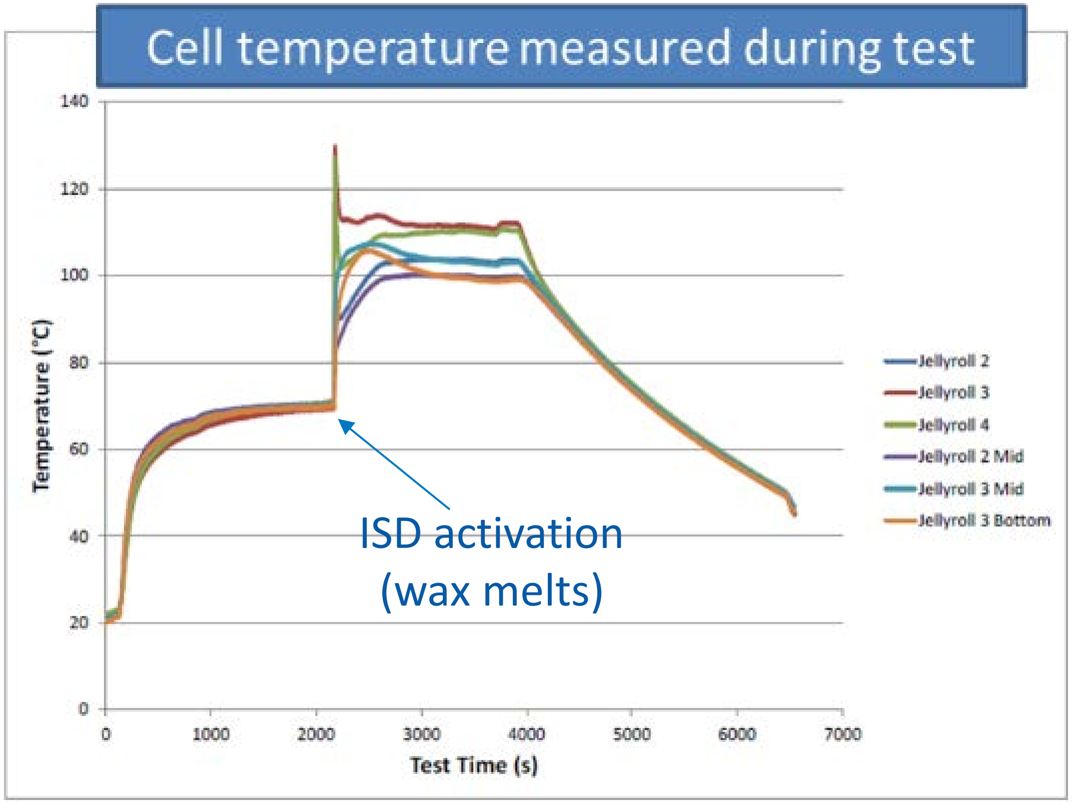
material with thermal quenching ability

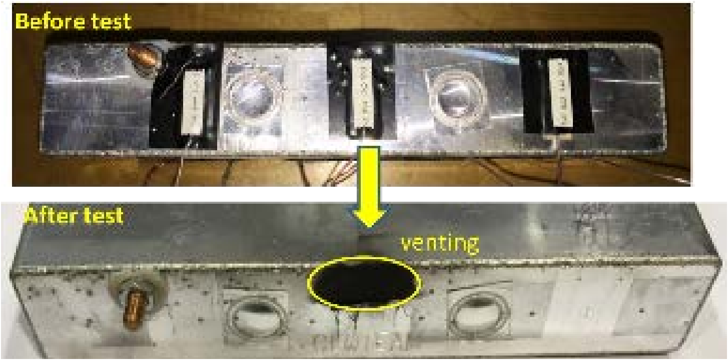
90 Ah “cell” consisting of 23 x 3.9Ah NCA jelly rolls

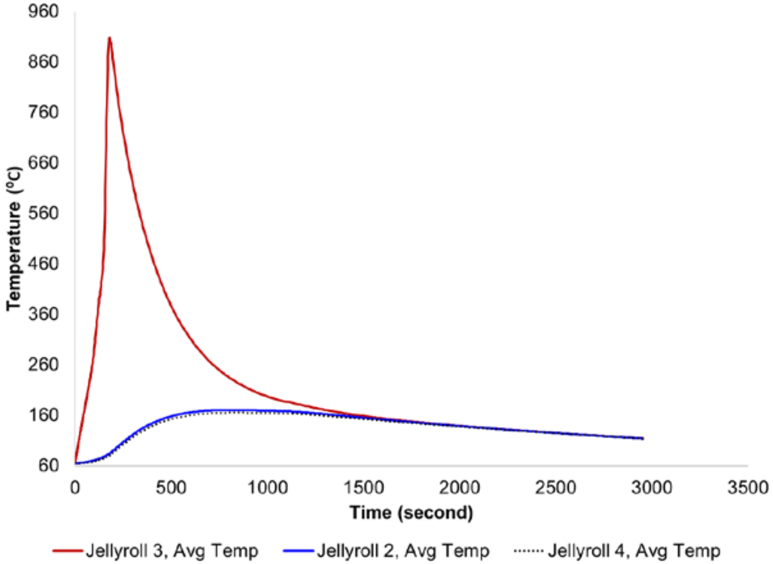


# Experiments Showed No TR Propagations

## for 30Ah NCM cell after initiating the internal short circuit



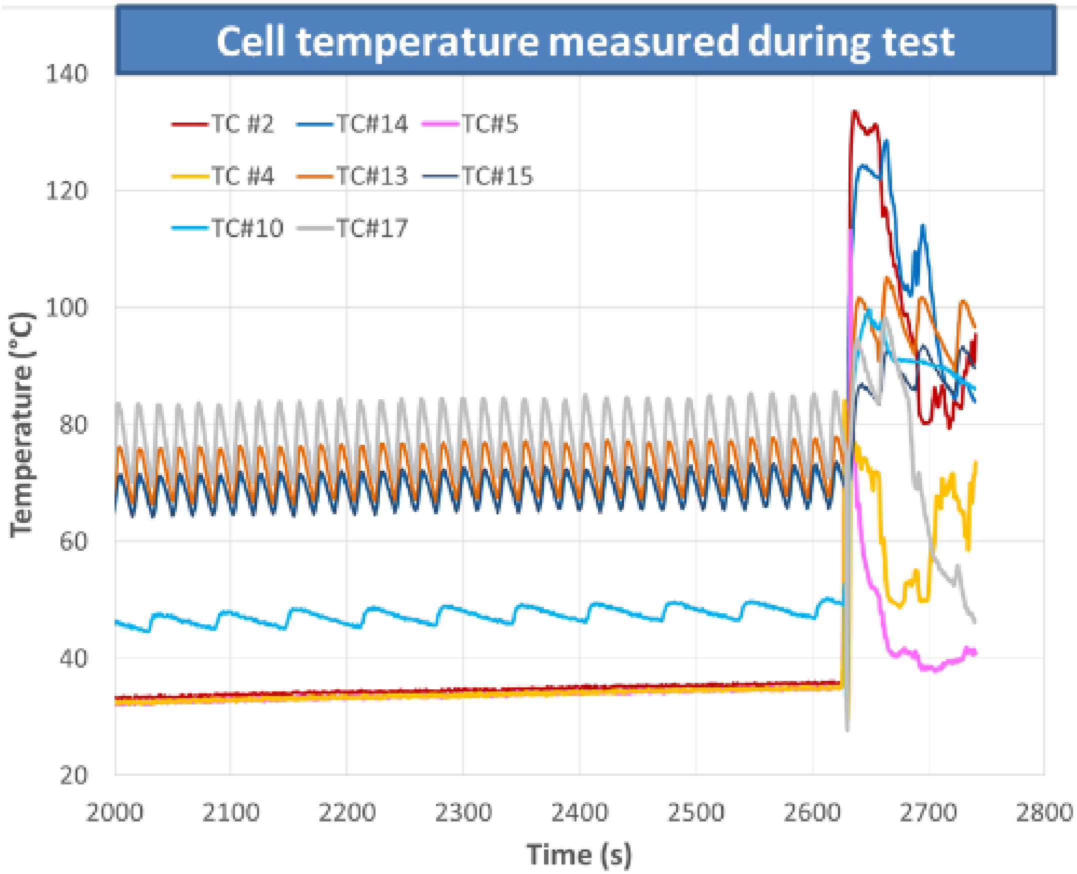




The cell only vented with a max measured cell surface temperature less than 138°C.

# Experiments Showed No TR Propagation

## in the 90 Ah cell after initiating the ISC (NCA)




**Front of cell after test**


The cell only vented with a max measured cell surface temperature less than 138°C.

# Summary – Battery Pack Thermal Design

- Battery thermal management system essential for xEVs
  - Normal operation during daily driving (achieving life and performance)
  - Off-normal operation during abuse conditions (achieving safety)
- Battery thermal management system needs to be optimized with right tools for lowest cost
- Experimental tools such as isothermal battery calorimeter, thermal imaging, and heat transfer setups are needed
- Thermal models and computer-aided engineering tools are useful for robust designs
- During abusive conditions, designs should prevent cell to cell propagation in a  module/pack (keep the fire small and manageable)
- NREL battery ISC device can be used for evaluating robustness of a module/pack to cell-to-cell propagation

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