National Renewable Energy Laboratory

Innovation for Our Energy Future

Electrothermal Analysis of Lithium Ion Batteries

Ahmad Pesaran
Andreas Vlahinos and Desikan Bharathan
National Renewable Energy Laboratory
Golden, CO, USA
ahmad_pesaran@nrel.gov, Tel: 303 275-4441

Tien Duong
U.S. Department of Energy
Washington, D.C., USA

THE 23rd INTERNATIONAL BATTERY SEMINAR & EXHIBIT
March 13 - 16, 2006
Fort Lauderdale, Florida

NREL/PR-540-39503

Disclaimer and Government License

Outline

- Introduction
- Approach (electrothermal modeling)
- Cells Analyzed
- Thermal Results
- Thermal Imaging
- Summary

Introduction

- One of the goals of DOE/FreedomCAR program is to develop high-power, safe, long-lasting and affordable batteries for various hybrid vehicle applications, including the 42V mild hybrids.
- With cost sharing from DOE/FreedomCAR, United State Advanced Battery Consortium (USABC) contracted Saft to develop a high-power, low-cost battery to meet the FreedomCAR technical targets for 42V M-HEV batteries (2003-2005).
- With support from DOE, NREL performed thermal analysis and testing for understanding and, if needed, improving thermal performance of cells supplied by the USABC program.

Description of Cells and FreedomCAR/USABC Goals

Features

- Very high power
- High energy density
- Maintenance free
- Long cycle life (over 1 million HEV shallow cycles)
- Projected 10 to 15 years calendar life.

Applications

- High power hybrid vehicles
- Any application requiring very high pulse power capability

Technology

- Graphite-based anode
- Nickel oxide-based cathode
- Electrolyte: blend of carbonate solvents + LiPF6

The latest Saft prototype cells meet most of the USABC/FreedomCAR performance goals.

USABC/FreedomCAR 42 V Energy Storage System End-of-Life Performance Goals

Characteristics	USABC Goal
Discharge Power (kW/2 sec.)	13
Regenerative Power (kW/2 sec.)	8
Engine-Off Accessory Load (kW/5 mm)	3
Available Energy (Wh at 3 kW)	300
Recharge Rate (kW)	2.6
Efficiency Load Profile (%)	90
Cycle Life, Miles/Profiles (Engine Start)	150K (450 K)
Load Profile	Partial Power Assist
Cold Cranking at –30°C/21V (kW)	8 --> 3
Calendar Life (Years)	15
Maximum System Weight (kg)	25
Maximum System Volume (l)	20
Selling Price ($/System at 100 K/Year)	260
Maximum OCV After 1 Sec. (Vdc)	48
Minimum Operating Voltage (Vdc)	27
Self-Discharge (Wh/Day)	Less than 20
Maximum Cell ΔT (°C)	N/A
Operating Temperature (°C)	-30 to +52
Survival Temperature (°C)	-46 to +66

Objectives of This Work

General

- Develop an electrothermal process/model for predicting thermal performance of real battery cells and modules.
- Use the electrothermal model to evaluate various designs to improve battery thermal performance.

This Study

- Use electrothermal model to predict the thermal behavior of two cell design iterations to identify improved thermal performance.
  - Design A: Saft Li-Ion Cylindrical with terminals on <u>opposite</u> sides.
  - Design B: Saft Li-Ion Cylindrical with terminals on the <u>same</u> side.

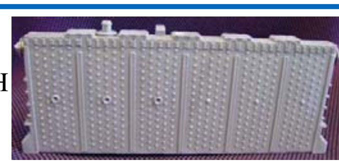
Motivation for the Thermal Analysis Work

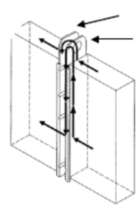
- Temperature greatly affects the performance and life (and thus warranty costs) of batteries.
- Battery thermal control/management is a must for hybrid electric vehicles under real driving conditions.
- Good battery pack thermal management starts with cells and modules that perform well thermally.
- Thermal modeling and simulation could aid in designing batteries with better thermal behavior.
- A 3-D model capturing electrical, as well as thermal behavior of batteries with real geometries and details including the non-electrochemical parts, was needed.

Analysis Approach

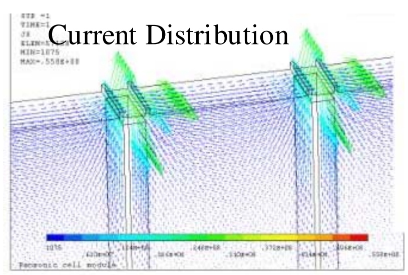
- Capturing details of a cell including non-electrochemical hardware with Finite Element Analysis.
- Estimating resistances of each component/part using geometry, materials, and test data.
- Applying voltage drop to calculate current density in components.
- Estimating resistive heating (I^2R) in each component.
- Applying electrochemical heat of reactions in the core (active parts).
- Applying heat transfer boundary conditions on cell exterior.
- Predicting temperature distribution in the cell from current density and related heat generation distribution.

Example: 6-cell Panasonic NiMH module

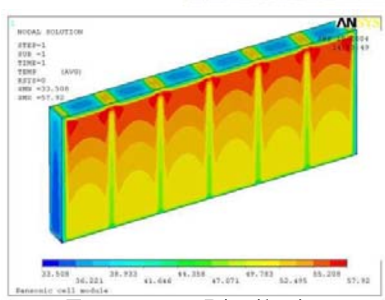




Two cells with an interconnect

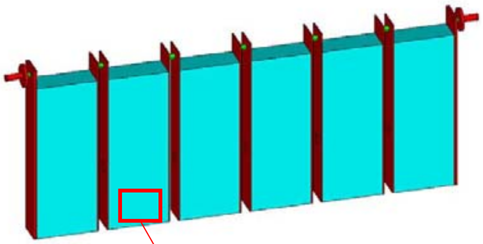


Current Distribution

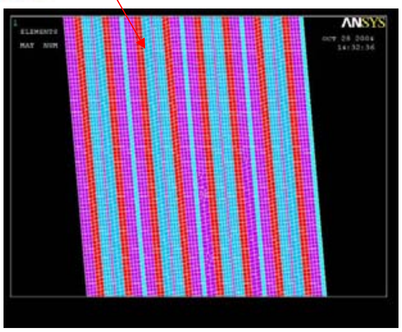


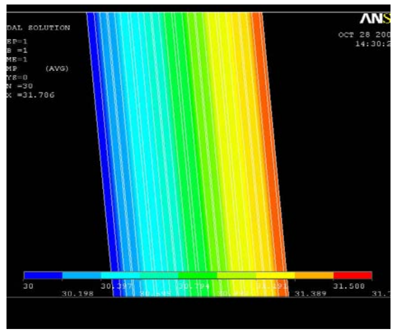
Temperature Distribution

Approximating Core/Winding Material



It's assumed that the core material (electrochemically active part) consisted of a homogenous material with average properties for resistivity and thermal conductivity, but with different properties in different directions (orthotropic xyz or rθZ)

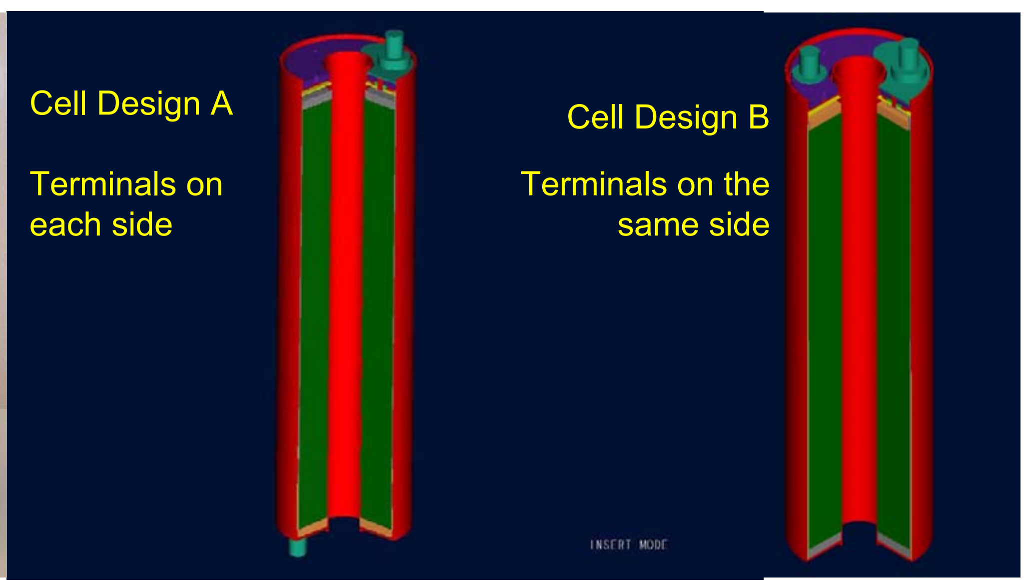




$$k_x = q * \Delta x / \Delta T$$
$$k_y = q * \Delta y / \Delta T$$
or
$$k_z = q * \Delta z / \Delta T$$
$$k_r = q * \Delta r / \Delta T$$

Used finite element analysis to calculate the effective thermal conductivity in each direction.

Physical Description of Cells Studied



Captured essential details of Cell Designs A and B

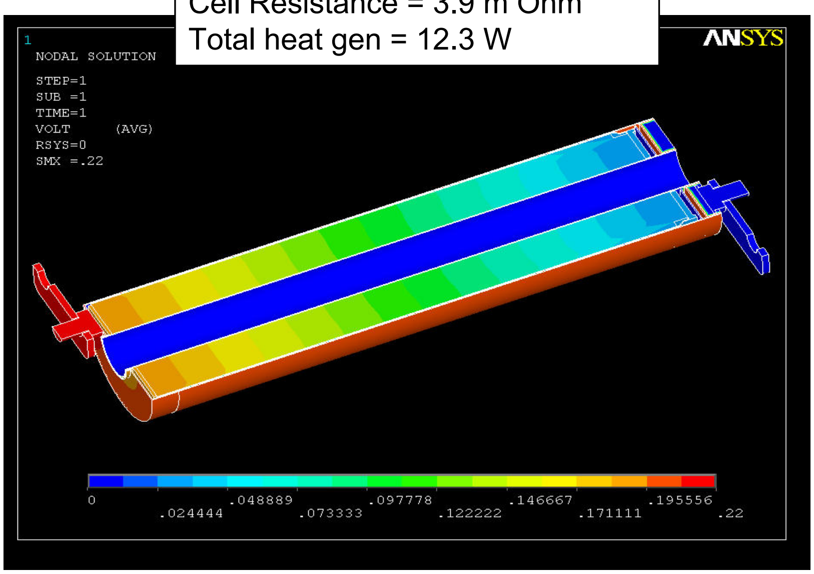
List of Assumptions and Approach

- Captured all geometry and material properties
  - All electrical resistivities from literature except for electrolyte/separator
  - Used experimental DC resistance of the cell to calculate resistivity of the winding
- Air cooling on all exterior surfaces
- Heat transfer film coefficient on all surfaces = 40 W/m^2K
- Initial battery and air temperature = 35^oC
- Target heat generation 12 W (based on heat generated under HPPC profile with HP12 LC cells at NREL calorimeter)
- Applied a voltage drop across the terminals; a current was created based on the electrical resistance of the cell.
- Voltage drop was adjusted so heat dissipation in the cell would be order of 12W.

Delta V = I * R   Heat Power = I * Delta V = R * I^2

Voltage Distribution – Cell Design A

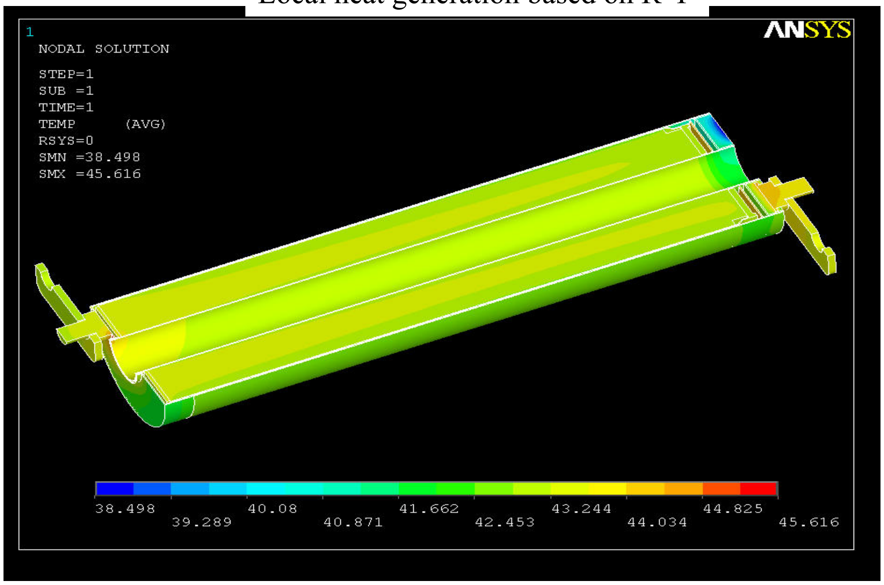
Delta V = 0.22 V
Current = 56 A
Cell Resistance = 3.9 m Ohm
Total heat gen = 12.3 W



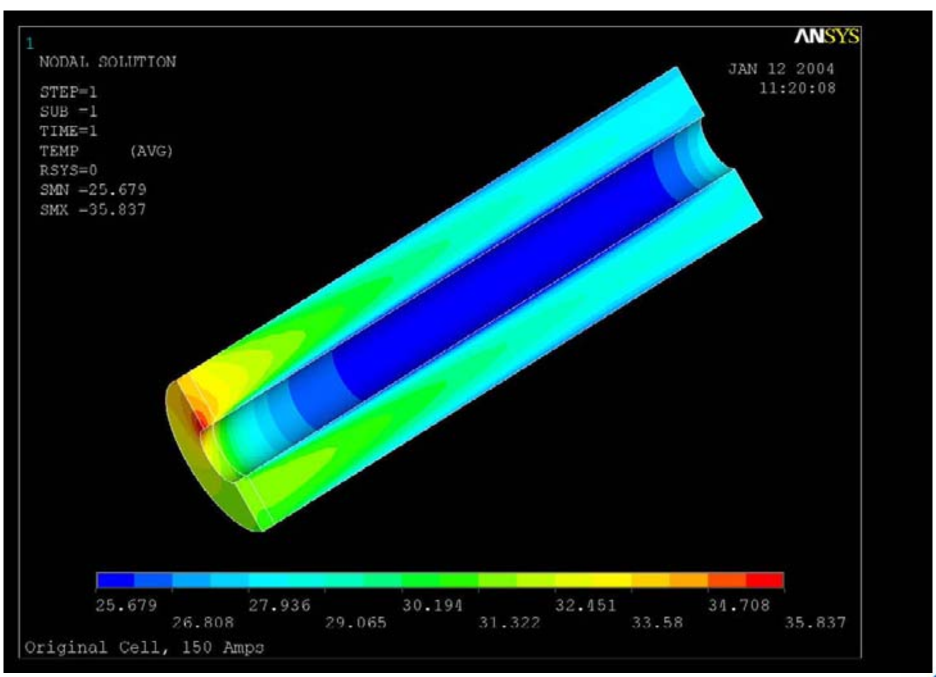
Temperature Distribution – Cell Design A

Total heat gen = 12.3 W

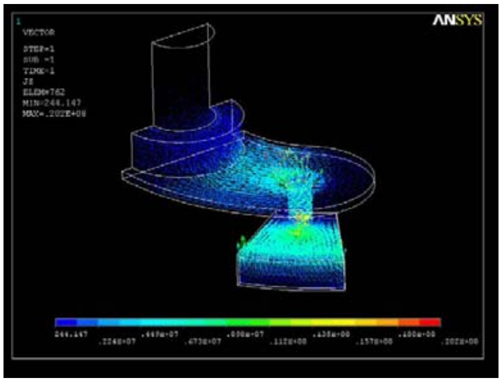
Local heat generation based on R*I²



Temperature Distribution in Winding Only Cell Design A

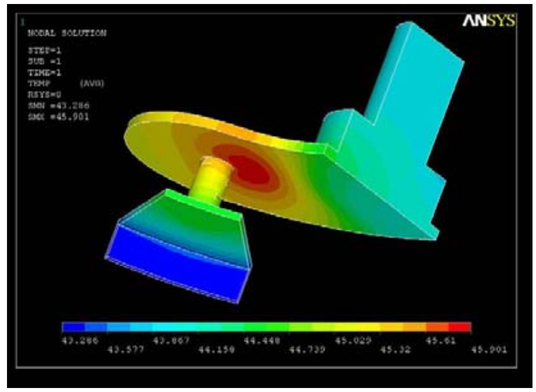


Results for Cell Design A (near +ve terminal)



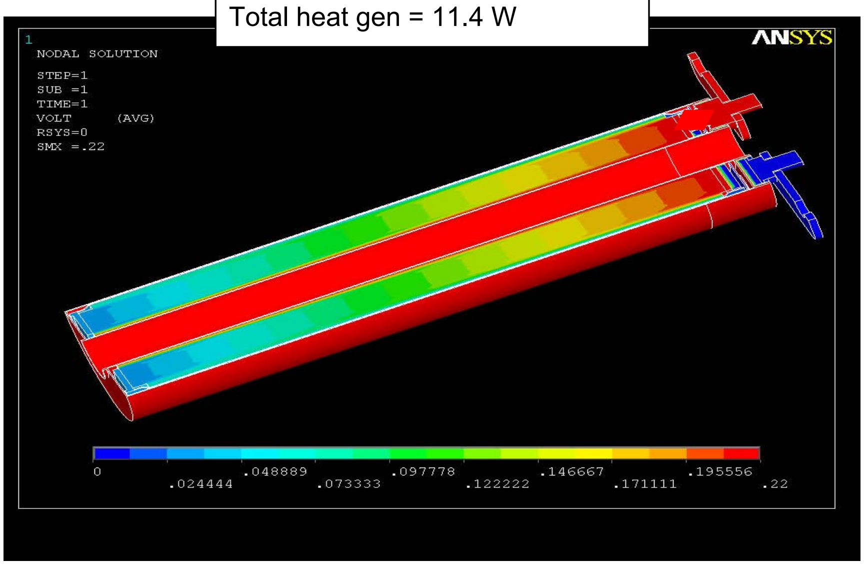
Current Density Distribution

Temperature Distribution

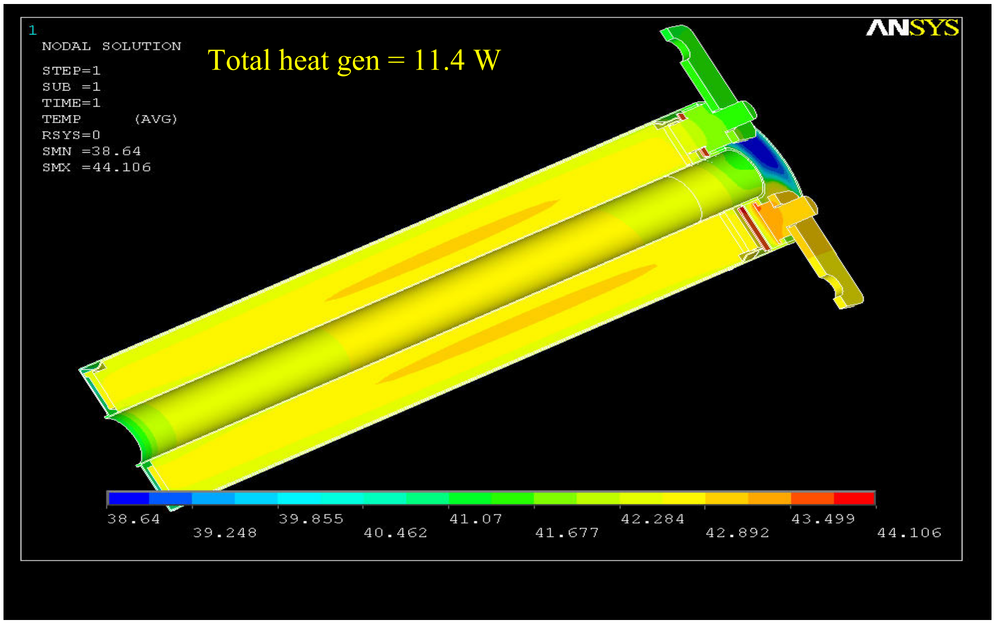


Voltage Distribution – Cell Design B

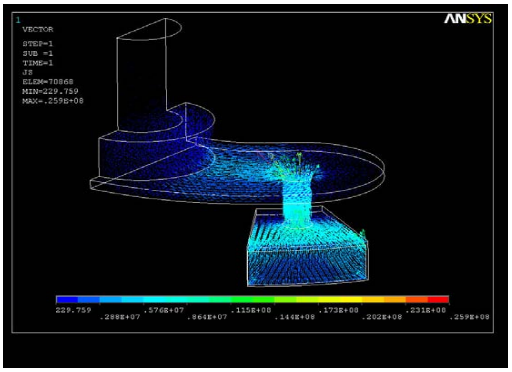
Delta V = 0.22 V
Current = 52 A
Cell Resistance = 4.23 m Ohm
Total heat gen = 11.4 W



Temperature Distribution – Cell Design B

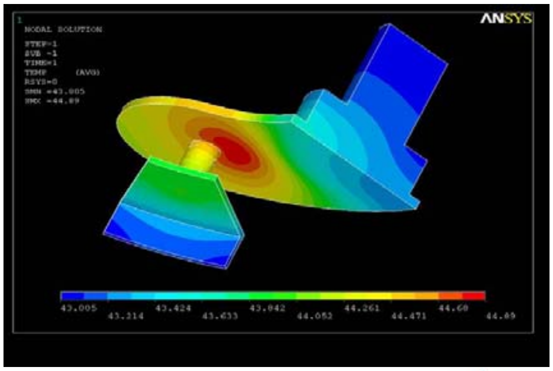


Results for Cell Design B (near +ve terminal)

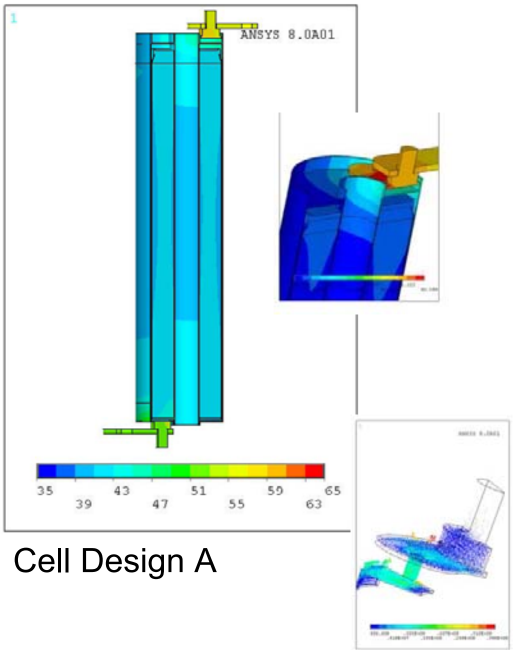


Current Density Distribution

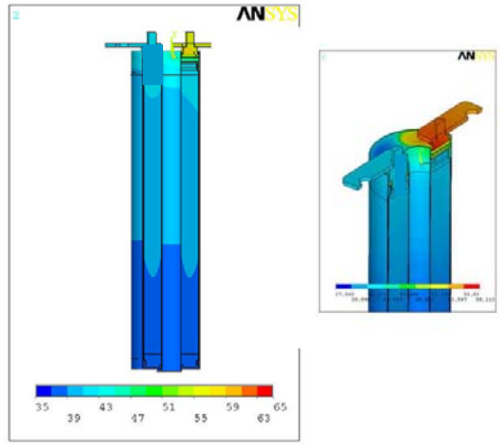
Temperature Distribution



Steady-State Results under "Average" of 110 Amp Load



Cell Design A



Cell Design B

Transient Analysis

Using P-HEV Heat Rejection Profile from FreedomCAR 42V Test Manual

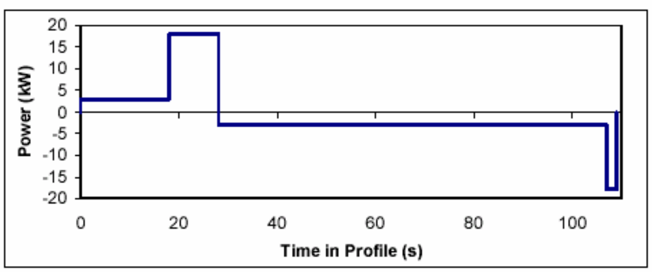
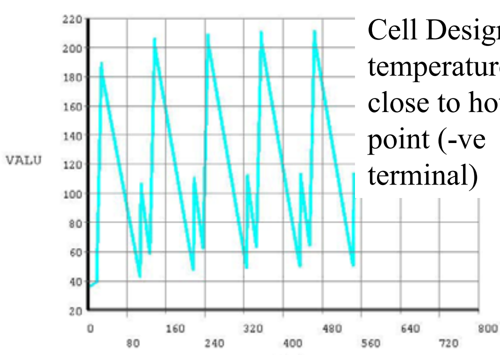
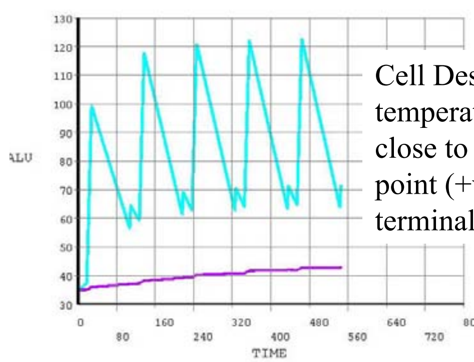


Figure 7. Heat Rejection Test Profile

Time (s)	Equivalent Current (A)
18	70
10	480
79	67
2	400

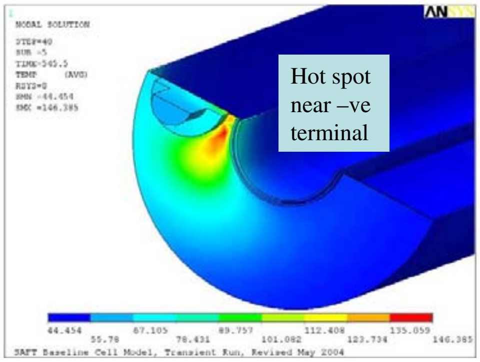


Cell Design A temperature close to hottest point (-ve terminal)

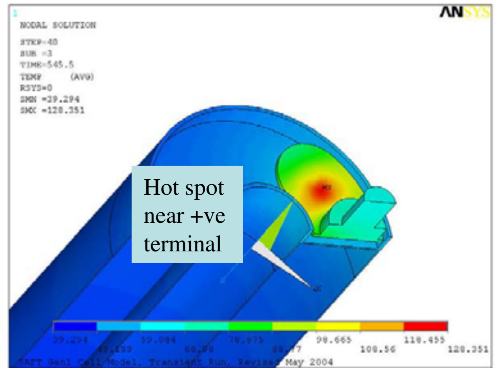


Cell Design B temperature close to hottest point (+ve terminal)

Cell Design A Exhibits Hotter Points near Terminal under the High Current Transients



Hottest spots in Cell Design A after 5 heat rejection test profiles



Hottest spots in Cell Design B after 5 heat rejection test profiles

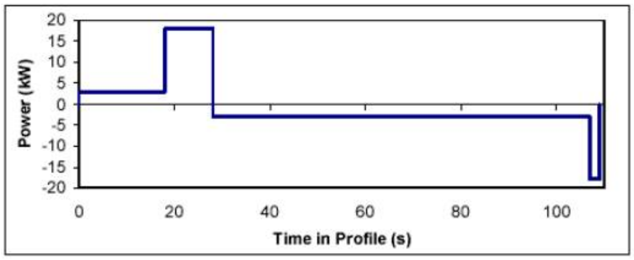


Figure 7. Heat Rejection Test Profile

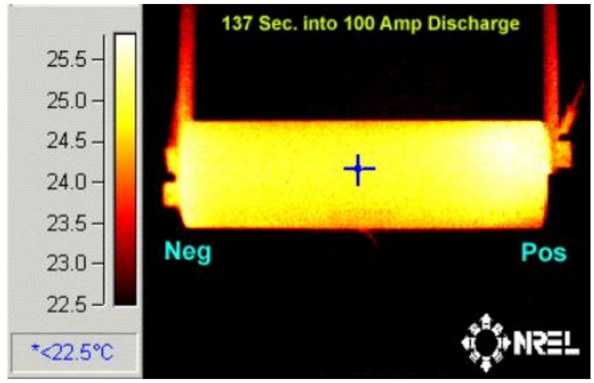
Summary of Electrothermal Analysis of Cells

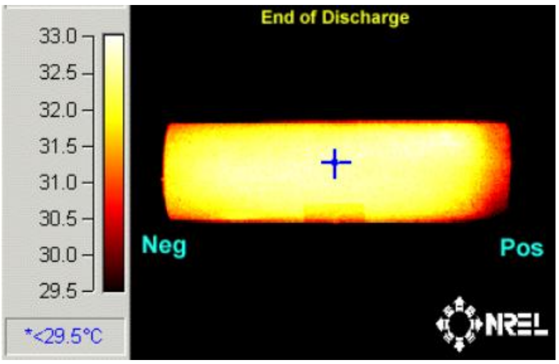
Temperature (ºC)	Cell Design A			Cell Design B		
Current	**110 Amps**	**166 Amps**	**5 cycles of Table 3**	**110 Amps**	**166 Amps**	**5 cycles of Table 3**
Maximum Hardware	60	93	146	58.1	88	128
Maximum Winding	43	53	66	42	50	48
Average Winding	~ 41	~ 49	~ 47	~ 39	~ 45	~ 44

- 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.

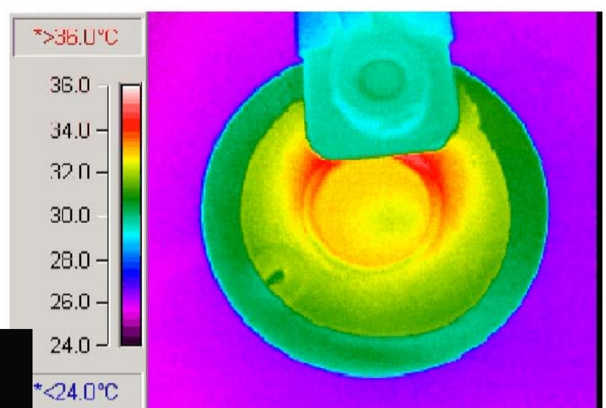
Thermal Imaging of Li-Ion Cells Confirms the Trends of Electrothermal Model

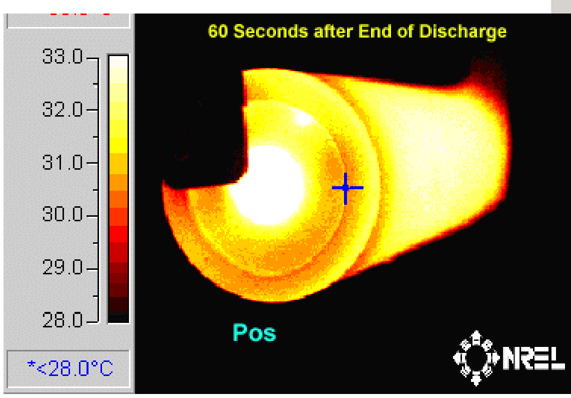
Thermal Imaging of a Saft Cell under 100 Amp Discharge





Thermal Imaging Showed Hot Spots near –ve Terminal for Cell Design A





Summary and Observations

- Developed an electrothermal modeling process for analyzing thermal performance of cells and batteries.
- The electrothermal model was used to evaluate thermal performance of two Li-Ion cylindrical cells.
  - The Cell Design A had a less favorable thermal performance under P-HEV transient heat rejection profile (hottest point near the negative weld).
  - The hottest point in Cell Design B was in the positive terminal.
  - The winding in Cell Design B was cooler than Cell Design A under the same current profile due to its lower resistance.
  - The trends of the electrothermal analysis were similar to the experimental thermal imaging results.
- The electrothermal analysis is a valuable tool for enhancing thermal and thus electrical performance and cycle/calendar life of Li-Ion batteries.

Acknowledgments

- DOE and FreedomCAR Program Support
  - Dave Howell
- USABC Technical Guidance
  - Bruce Blakemore