Electrothermal Analysis of Lithium Ion Batteries

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

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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.

NREL

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 + $LiPF_6$

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 □T (°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.

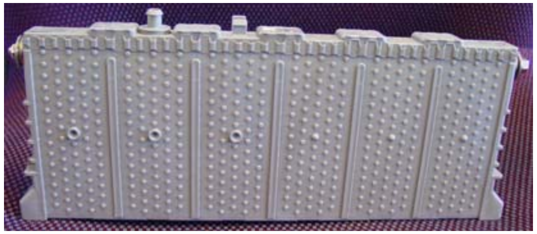
Motivation for the Thermal Analysis Work

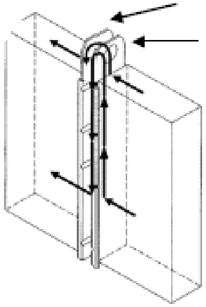
- Temperature greatly affects the performance and life (and thus warranty costs) of batteries.
- Battery thermal control/management is a must for hybrid electric vehicles under real driving conditions.
- Good battery pack thermal management starts with cells and modules that perform well thermally.
- 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

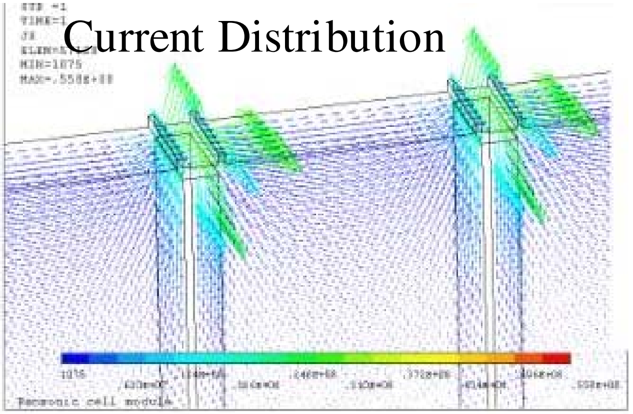
- Capturing details of a cell including non-electrochemical hardware with Finite Element Analysis.
- Estimating resistances of each component/part using geometry, materials, and test data.
- Applying voltage drop to calculate current density in components.
- Estimating resistive heating (I^2R) in each 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

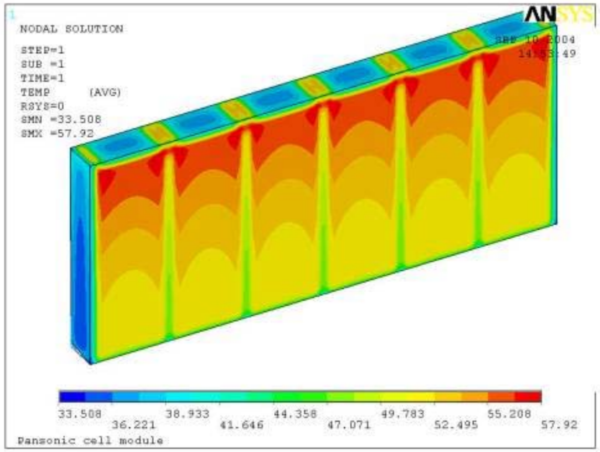




Two cells with an interconnect

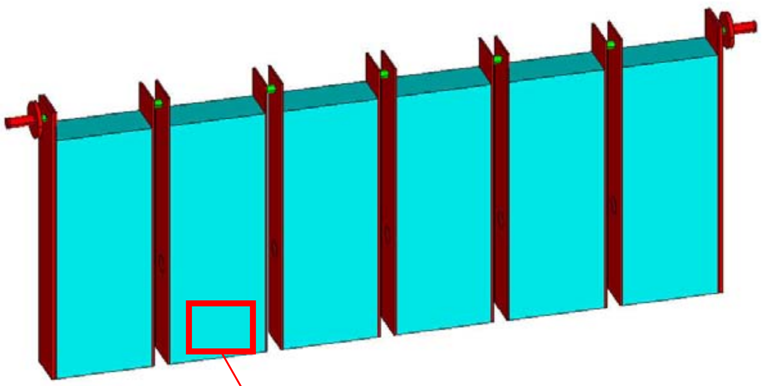


Current Distribution

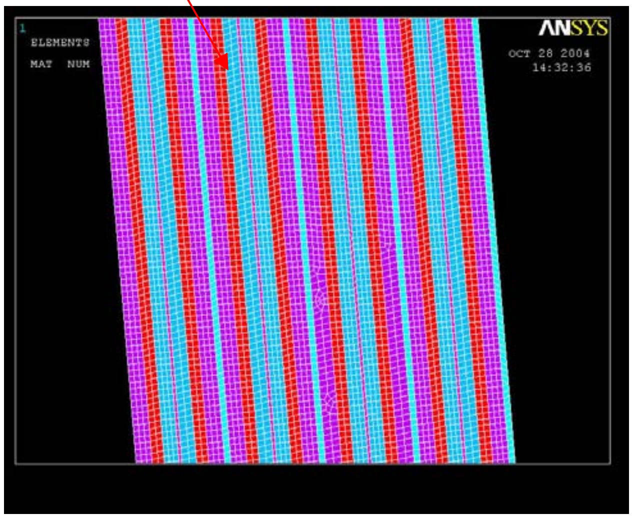


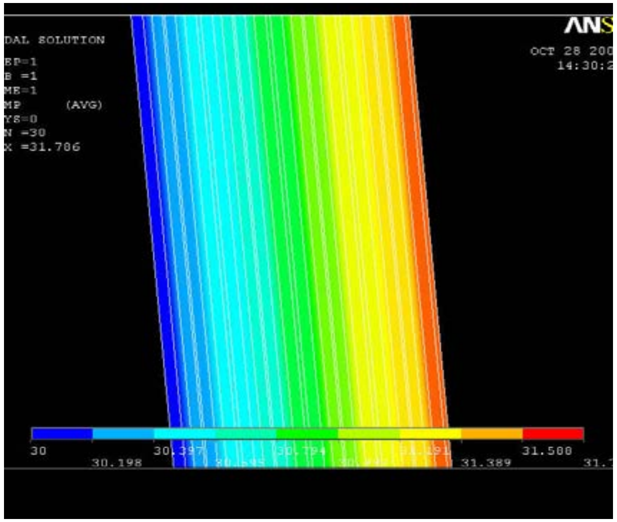
Temperature Distribution

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)





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

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

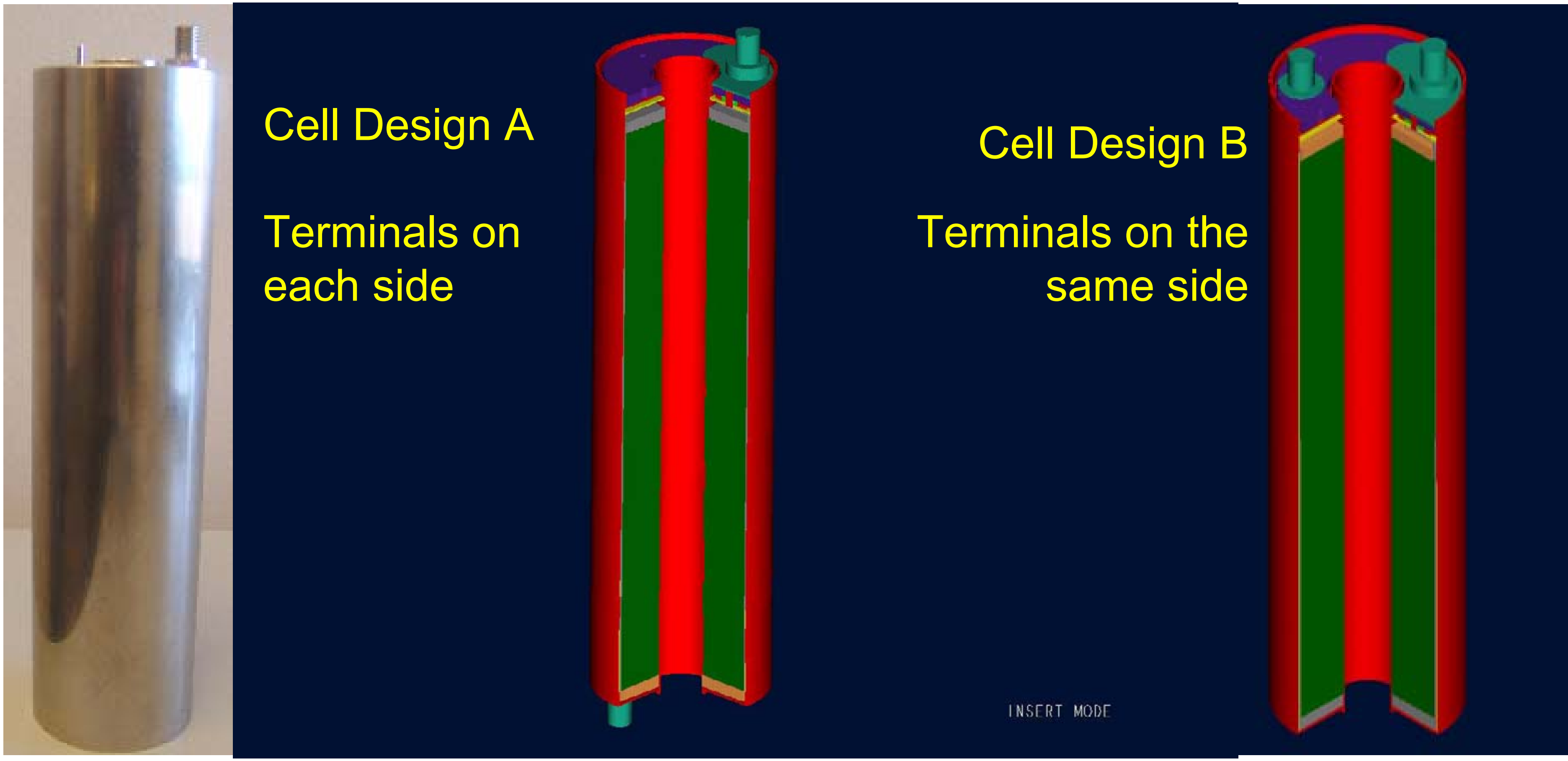
or

$$k_z = q * \Delta z / \Delta T$$

$$k_r = q * \Delta r / \Delta T$$

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

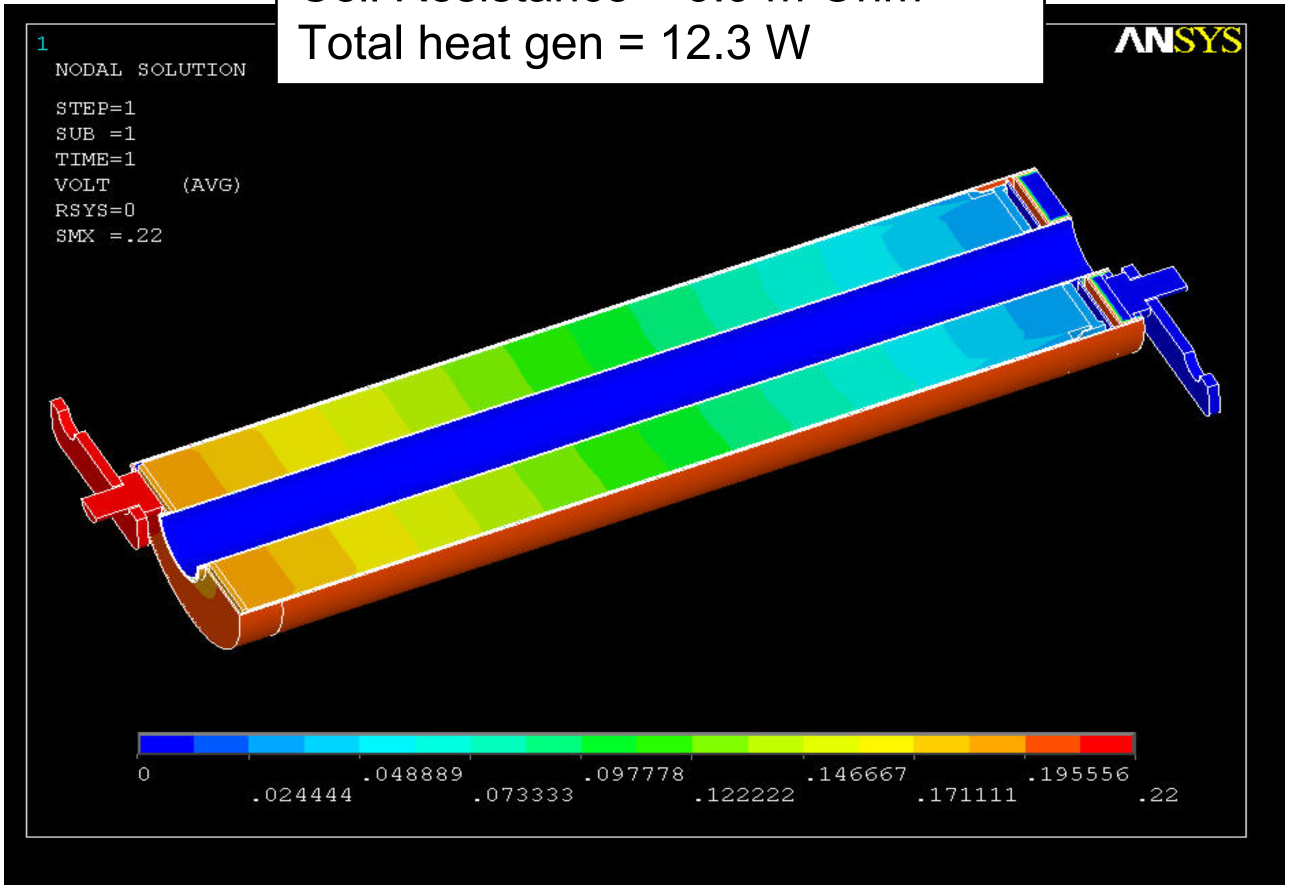
List of Assumptions and Approach

- 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.

$$\text{Delta V} = I * R \qquad \text{Heat Power} = I * \text{Delta V} = R * I^2$$

Voltage Distribution – Cell Design A

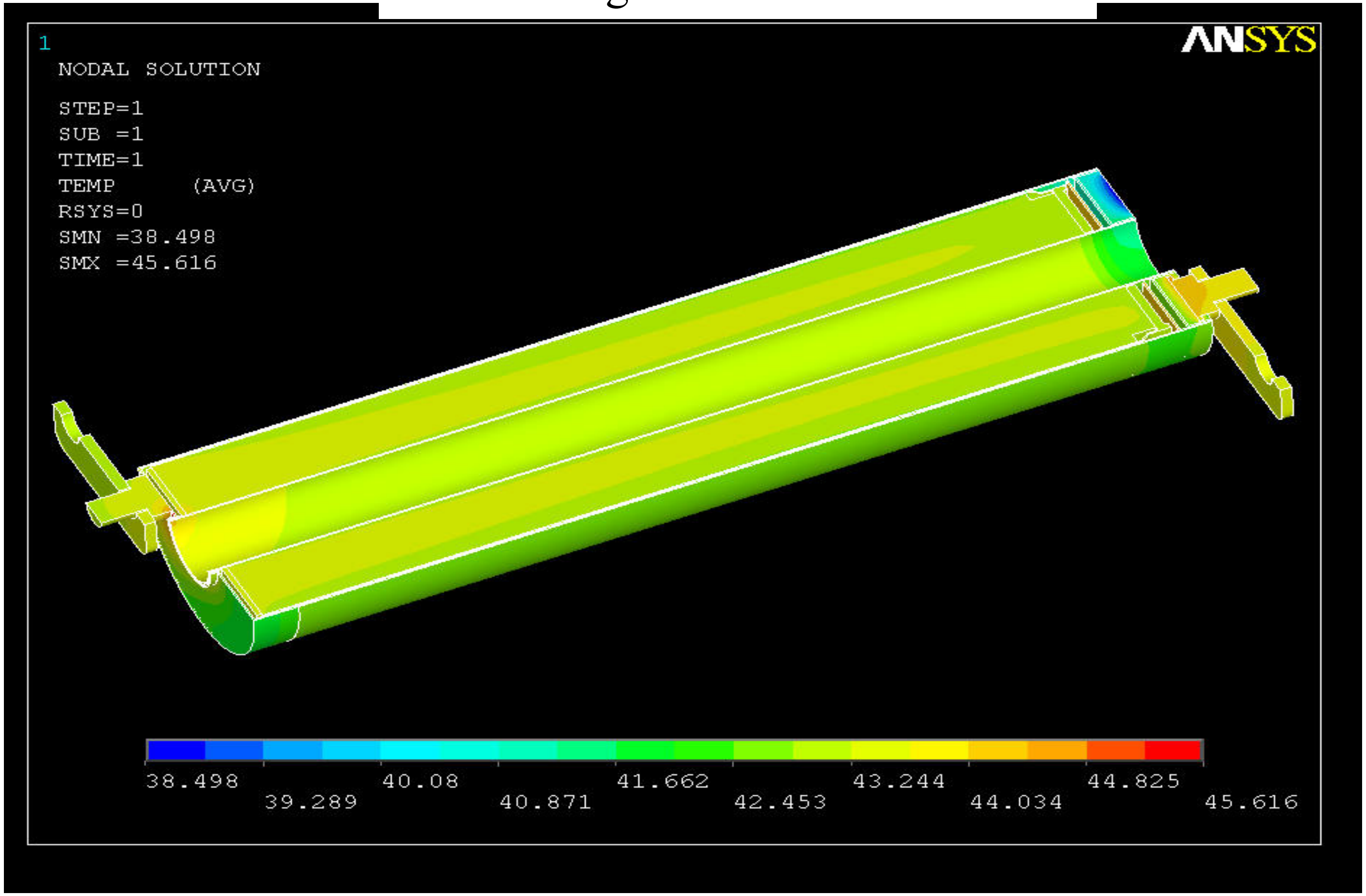
Delta V = 0.22 V
Current = 56 A
Cell Resistance = 3.9 m Ohm
Total heat gen = 12.3 W



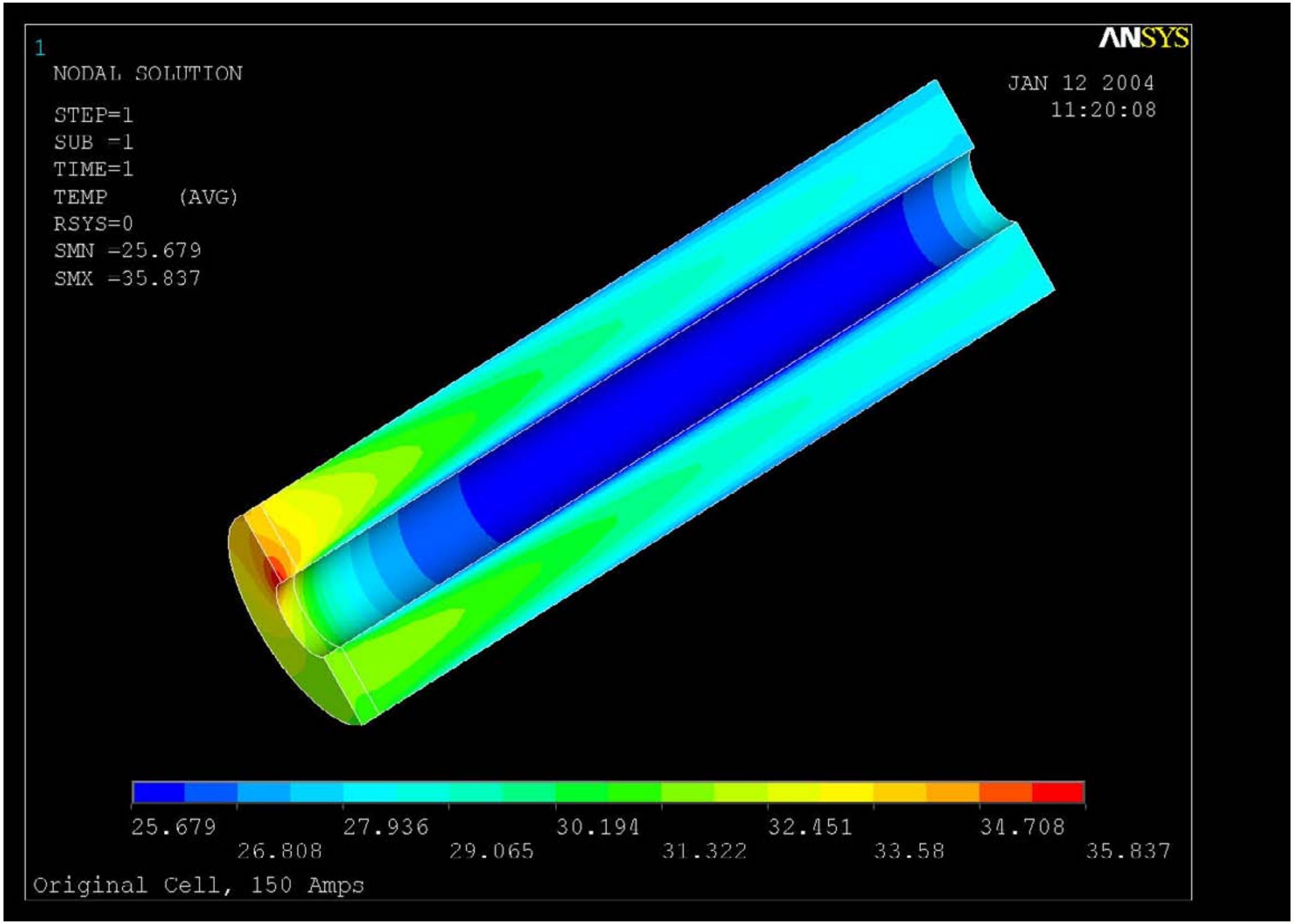
Temperature Distribution – Cell Design A

Total heat gen = 12.3 W

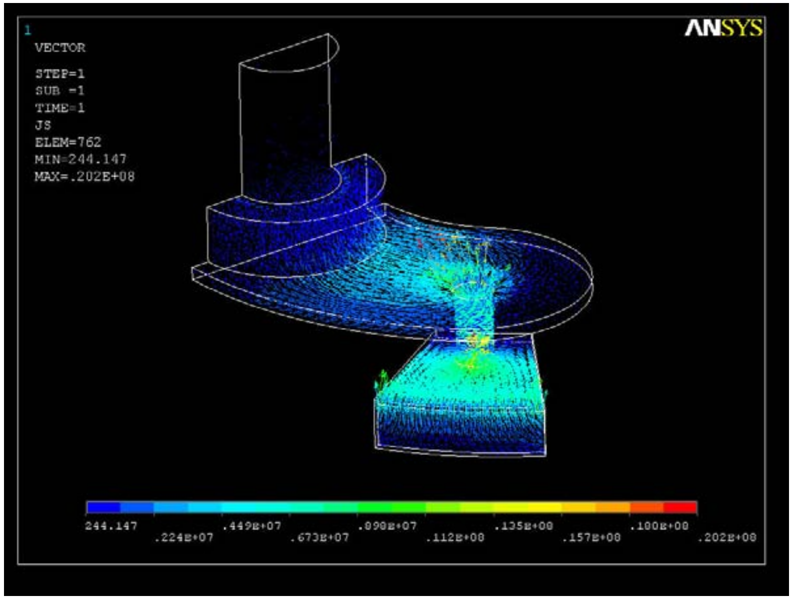
Local heat generation based on $R*I^2$



Temperature Distribution in Winding Only
Cell Design A

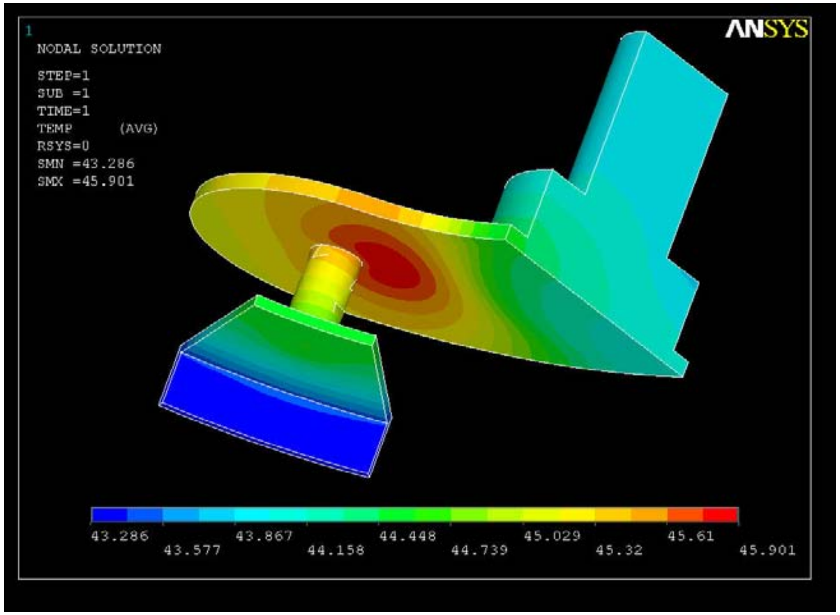


Results for Cell Design A (near +ve terminal)



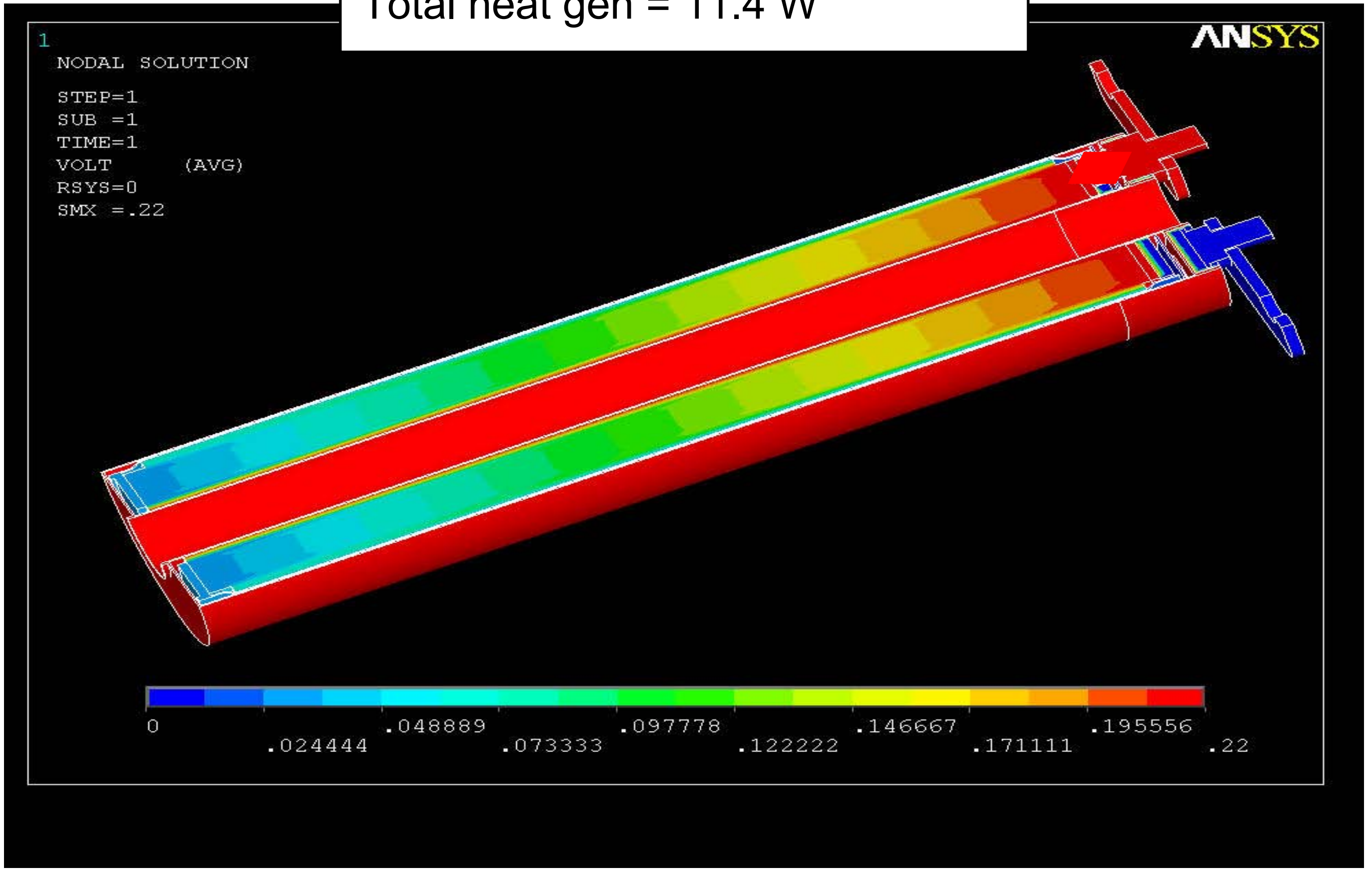
Current Density Distribution

Temperature Distribution

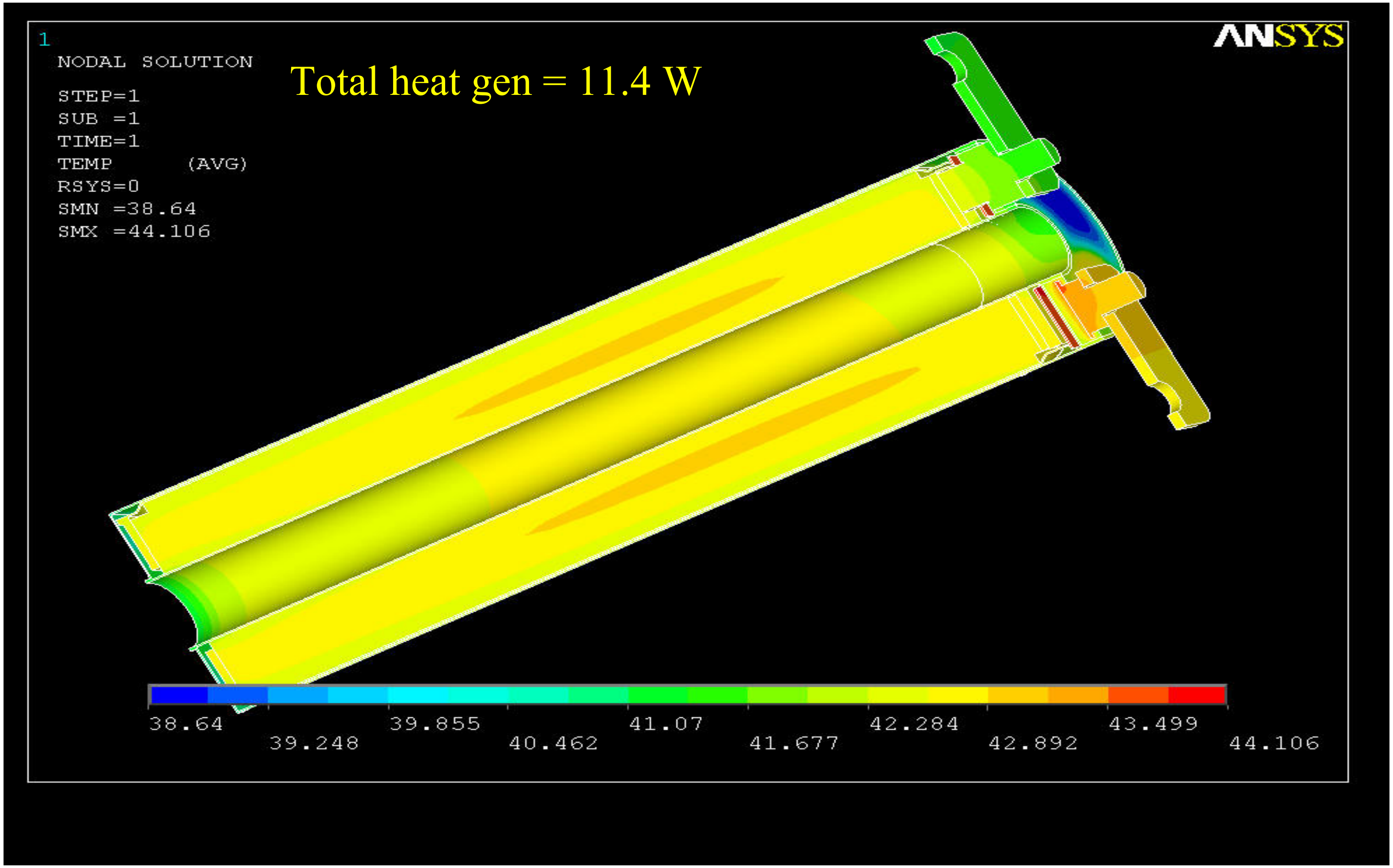


Voltage Distribution – Cell Design B

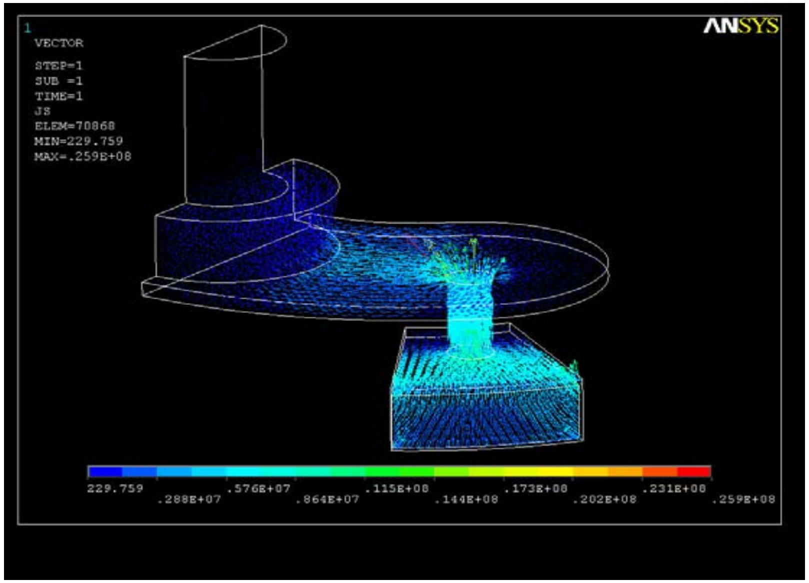
Delta V = 0.22 V
Current = 52 A
Cell Resistance = 4.23 m Ohm
Total heat gen = 11.4 W



Temperature Distribution – Cell Design B

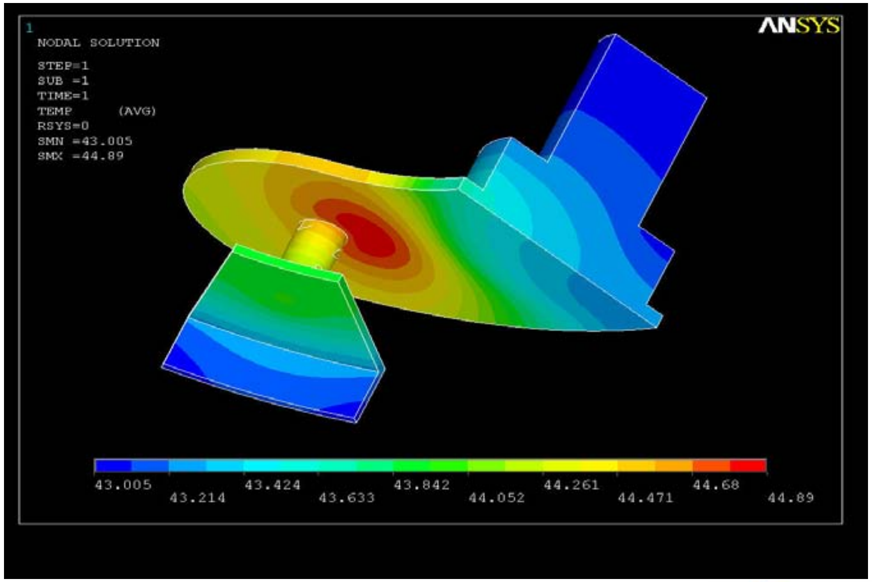


Results for Cell Design B (near +ve terminal)

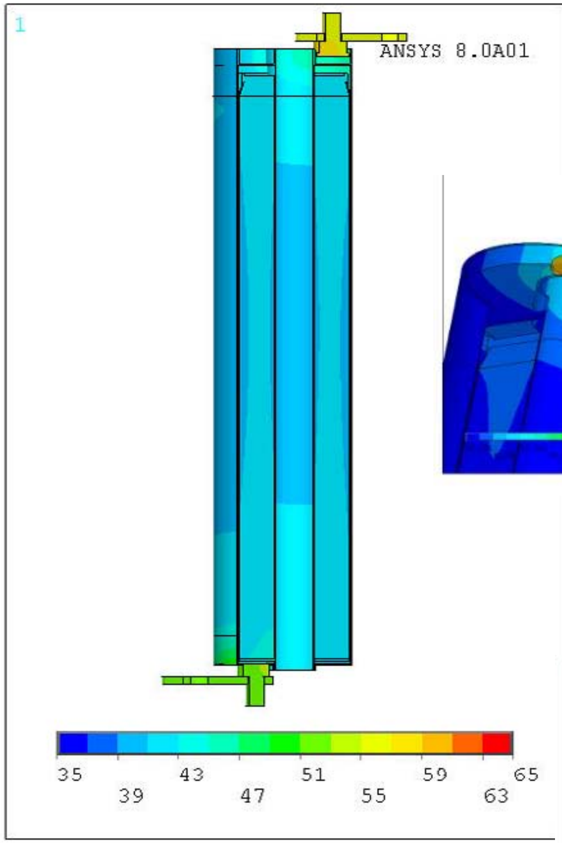


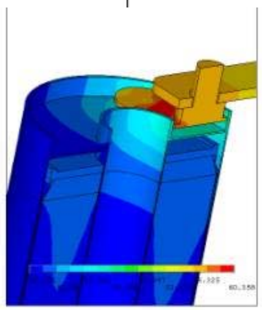
Current Density Distribution

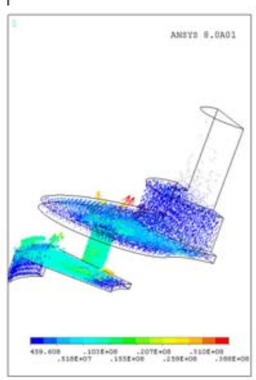
Temperature Distribution



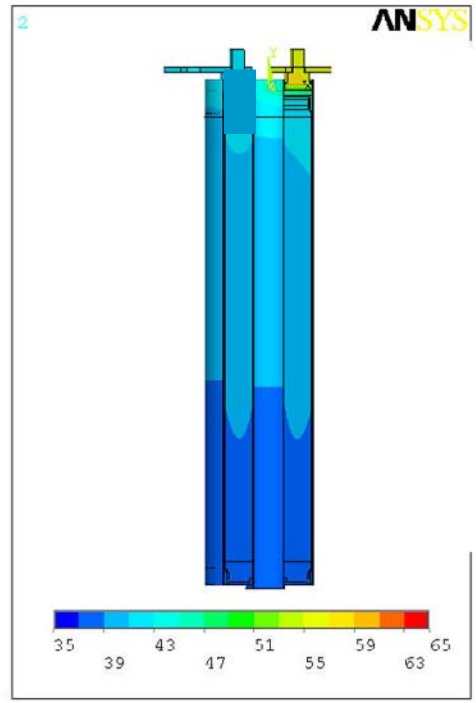
Steady-State Results under “Average” of 110 Amp Load

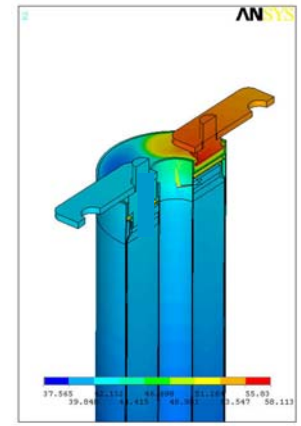






Cell Design A





Cell Design B

Transient Analysis

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

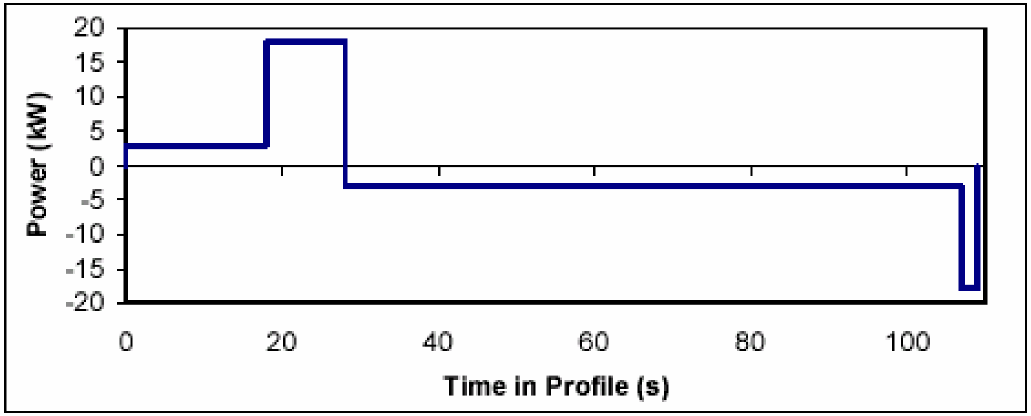
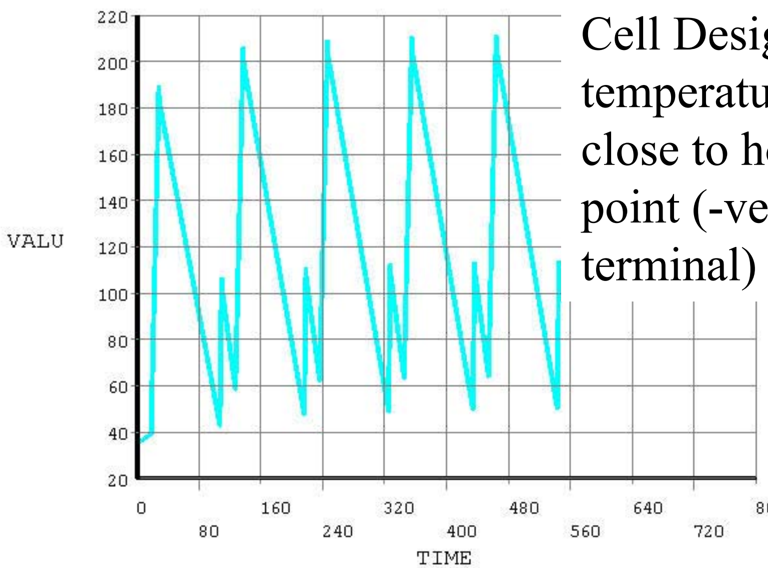
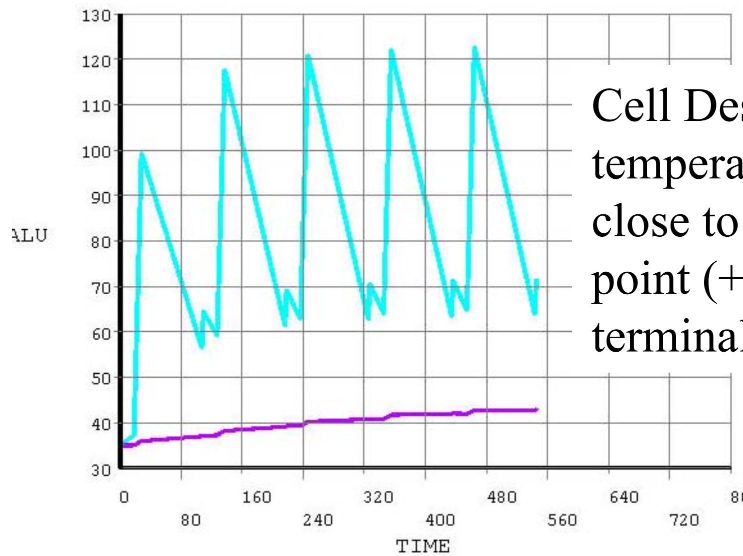


Figure 7. Heat Rejection Test Profile

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

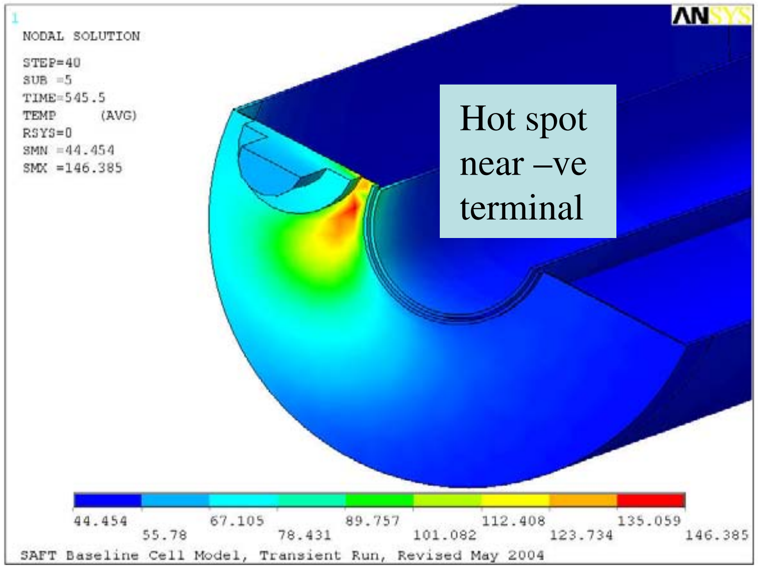


Cell Design A temperature close to hottest point (-ve terminal)

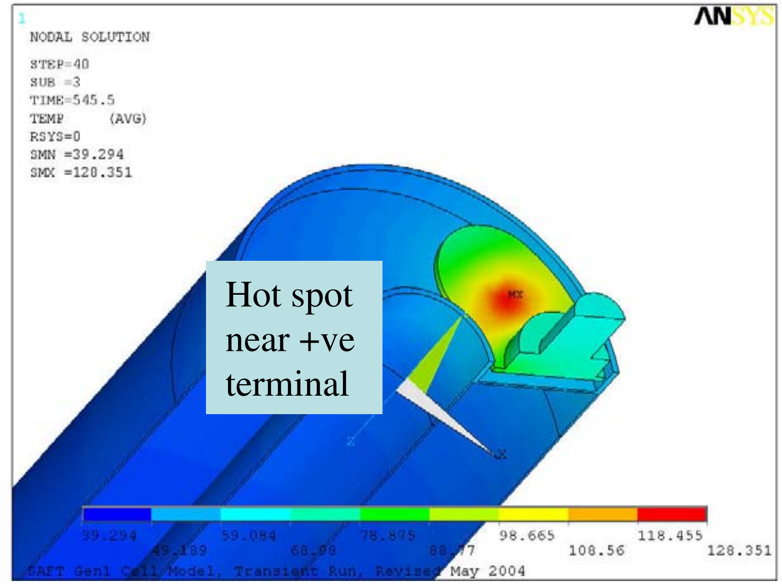


Cell Design B temperature close to hottest point (+ve terminal)

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

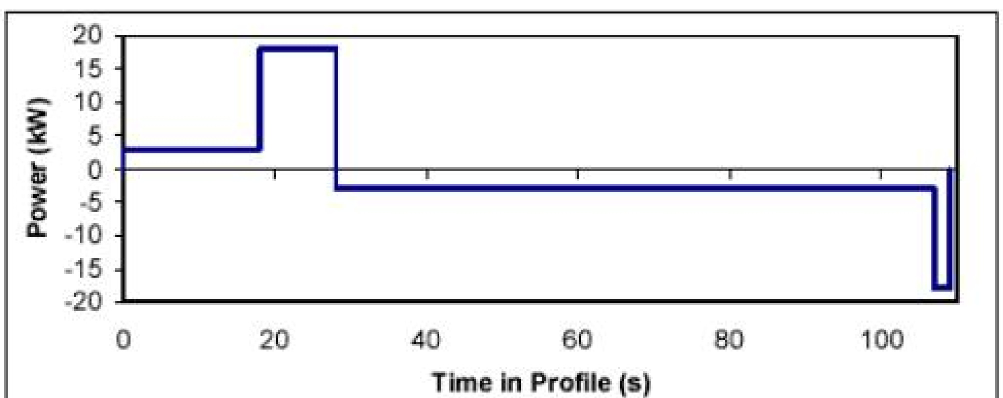


Figure 7. Heat Rejection Test Profile

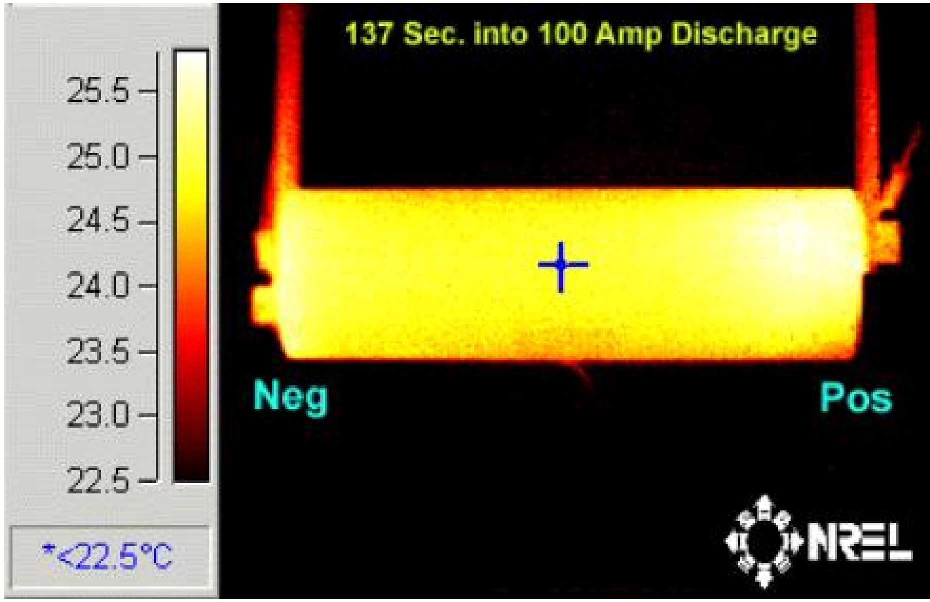
Summary of Electrothermal Analysis of Cells

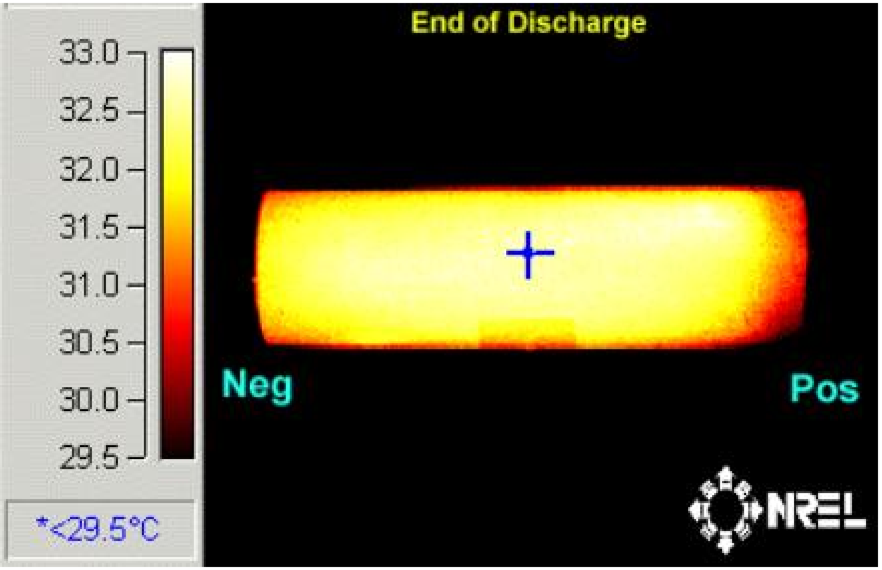
Temperature (ºC)	Cell Design A			Cell Design B		
Current	**110 Amps**	**166 Amps**	**5 cycles of Table 3**	**110 Amps**	**166 Amps**	**5 cycles of Table 3**
Maximum Hardware	60	93	146	58.1	88	128
Maximum Winding	43	53	66	42	50	48
Average Winding	~ 41	~ 49	~ 47	~ 39	~ 45	~ 44

- 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.

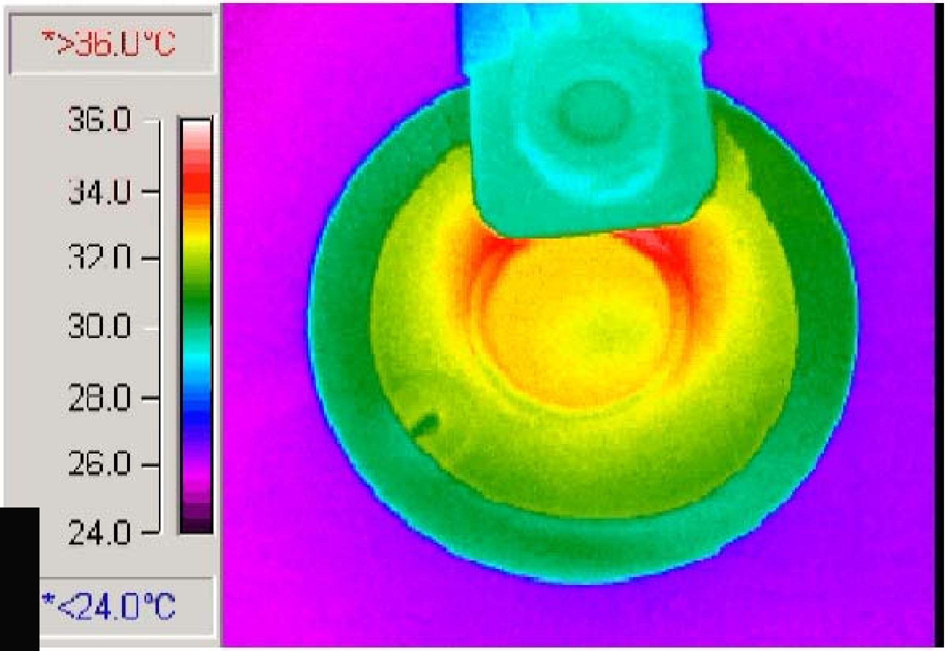
Thermal Imaging of Li-Ion Cells Confirms the Trends of Electrothermal Model

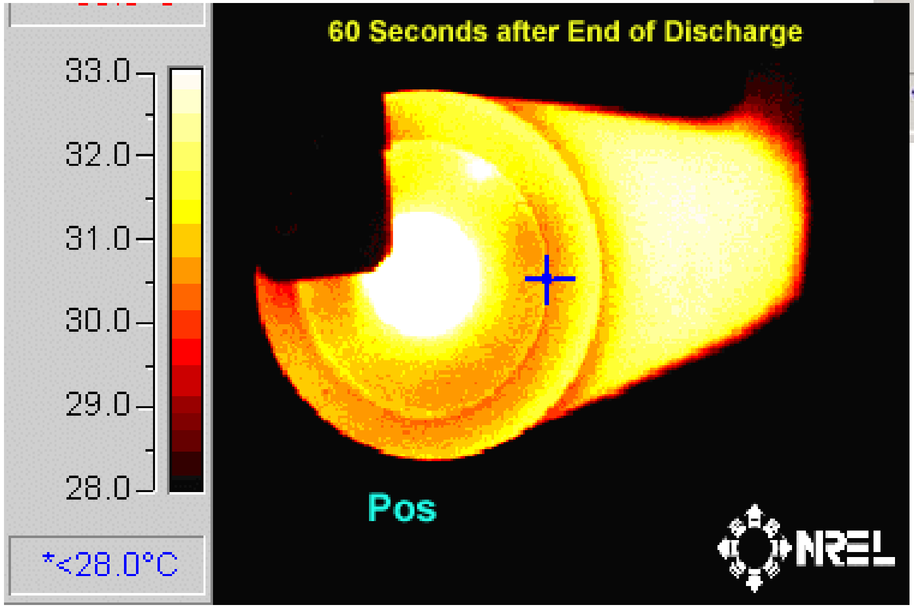
Thermal Imaging of a Saft Cell under 100 Amp Discharge





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