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Electro-Thermal Modeling to Improve Battery Design

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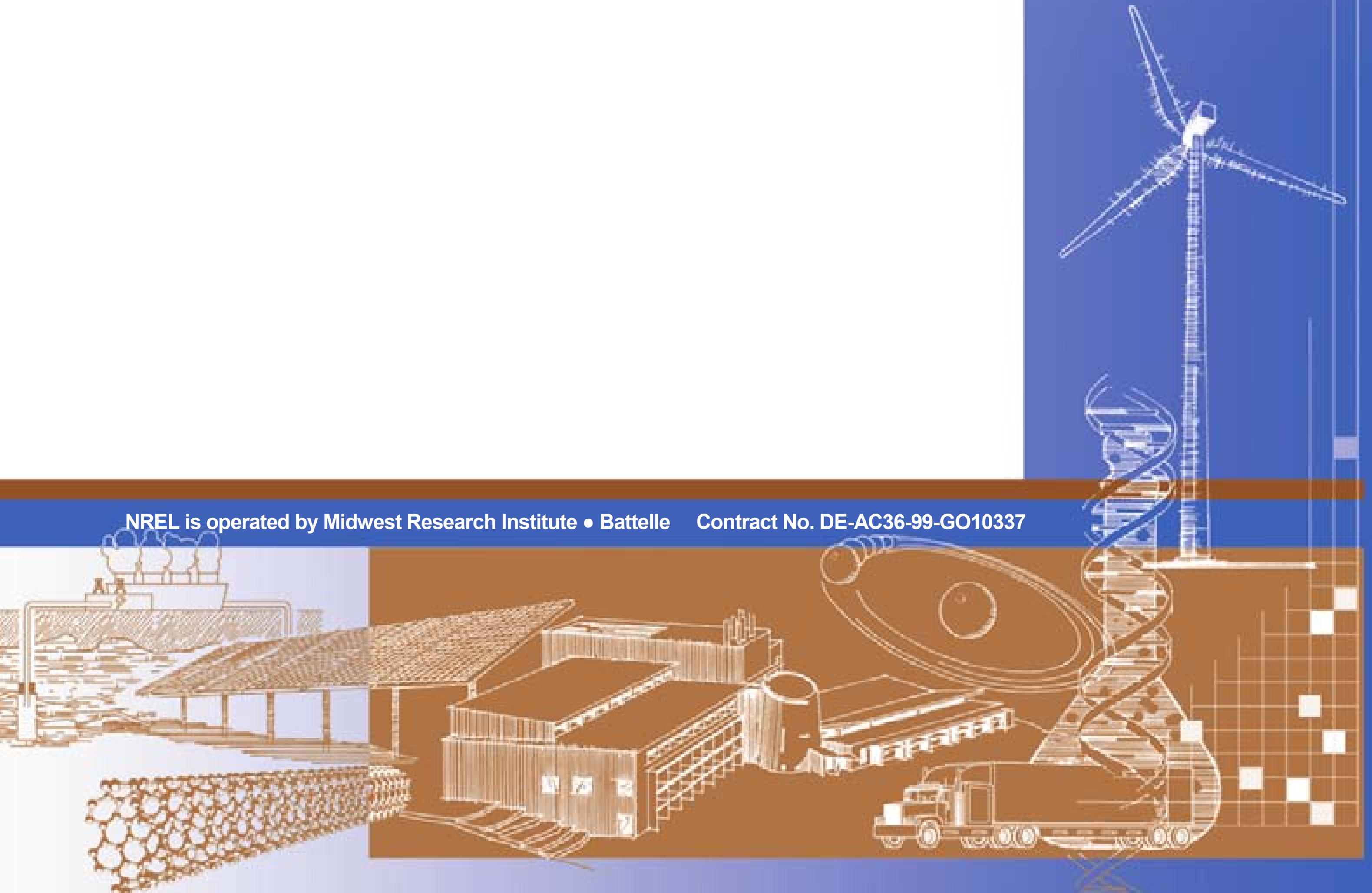

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Electro-Thermal Modeling to Improve Battery Design

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Abstract

Operating temperature greatly affects the performance and life of batteries in electric and hybrid electric vehicles (HEVs). Increased attention is necessary to battery thermal management. Electrochemical models and finite element analysis tools are available for predicting the thermal performance of batteries, but each has limitations. In this study we describe an electro-thermal finite element approach that predicts the thermal performance of a battery cell or module with realistic geometry. To illustrate the process, we simulated the thermal performance of two generations of Panasonic Prismatic nickel-metal-hydride modules used in the Toyota Prius HEV. The model showed why the new generation of Panasonic modules had better thermal performance than the previous 2001 modules Thermal images from the two battery module generations, under constant current discharge, indicate that the model predicts the experimental trend reasonably well.

Keywords: HEV (hybrid electric vehicle), thermal management, nickel metal hydride, battery model, simulation, electro-thermal finite element

1 Introduction

Temperature greatly affects the performance and life of batteries, so battery thermal control is necessary in a hybrid electric vehicle (HEV) under real driving conditions. In recent years, automakers and battery suppliers have paid increased attention to battery thermal management, especially with regard to life cycle and related warranty costs. A thermal management system could be designed ranging from “simple energy balance equations” to more “sophisticated thermal and computational fluid dynamic models.” However, the basic performance of the management system is dictated by the thermal design of each cell or module. So it is critical to design cells and modules that have inherently good thermal performance. Sophisticated electrochemical models are available for predicting the performance of electrochemical cells [1 and 2], but they cannot capture the heat transfer aspects of the actual geometry with cell or module hardware (case, terminal posts, connectors, interconnects, relief valves, current collectors, seals, etc). Some finite element models can capture geometry [3 and 4], but cannot capture heat generation resulting from passage of currents in various components. In the past, we have used ANSYS commercial finite element analysis software, which captured the thermal aspects only [3]. The heat generation was added by estimating the ohmic heating and enthalpies of electrochemical reactions and applying that heat to the entire cell core.

For this study, we focused on integrating the electrical aspects of the cells and modules (including the cell hardware) into a finite element thermal analysis model. Our goals were to (1) develop the electro-thermal process or model for predicting thermal performance of cells and modules; (2) apply the model to predict the thermal performance of a baseline design (such as the 2001 Panasonic nickel-metal-hydride [NiMH] module) and compare it to the performance of a next-generation design (2004 Panasonic NiMH module); and (3) compare the predictions with infrared thermal imaging of modules under similar conditions.

2 Approach

It is particularly challenging to capture and model all the physical elements and details of a cell and drive the design parametrically for simultaneous electrical and thermal (electro-thermal) modeling, while considering performance limits and specifications for optimum efficiency and cost considerations. The process of engineering optimization via highly connected computer-aided engineering approaches is considered to be the best method, but it is not standard industry practice. During this project, we worked closely with a battery developer to develop such a tool. If the cell design is complicated, we use ProEngineer (ProE) software, a computer-aided design (CAD) tool, to build a detailed virtual model of a cell or module. The CAD model consists of the cell core (positive electrode, negative electrode, separator, and electrolyte), the cell or module case, internal connectors from the core to the terminals, connectors to posts of terminals, and (in the case of a module) cell-to-cell interconnects.

We assume that the core (the electrochemically active part of the cell) is orthotropic—a homogenous combination of all its elements, but with different thermal and electrical properties in different directions. The CAD model is transferred to ANSYS to create a finite element model that can perform both electrical and thermal analysis. If the design of the cell is simple, we use ANSYS to capture the geometry and details of the cell or module. Once the geometry and material properties are specified, ANSYS can calculate the electrical resistance of each component. The resistivity of any unknown components can be adjusted to match measured resistance of the cell. A current flows through the cell when a potential difference is applied across the two terminals. This causes Joule heating that increases the temperature of all components. The heat caused by the electrochemical reactions is included as needed. ANSYS uses the heat generated to estimate the temperature distribution in the cell. Hot spots can be readily identified during steady-state and /or transient loads.

To our knowledge, this is the first time that this type of electro-thermal analysis process has been applied to cells. A designer can use this approach to improve the thermal performance of batteries by reducing resistances, improving the power capability, and avoiding hot spots in cells that could lead to premature failures.

3 Modeling and Results

We applied the electro-thermal process to the Panasonic Prismatic NiMH module used in the 2001 Toyota Prius HEV and compared it with the new Panasonic module used in the 2004 Prius. Figure 1 shows a diagram and picture of the 2001 Panasonic module, which has 6 cells, with total capacity of 6.5 Ah, module voltage of 7.2 V, and power capability of 1000 W/kg [5]. Figures 2 and 3 show the associated finite element model. Using the electro-thermal process, we captured six cores, cell-to-cell interconnects, weld junction, current collectors, and terminals. We ignored the dimples on the surface of the case, but captured their impact with an adjusted heat transfer coefficient on the case. We made assumptions for properties of each material based on our understanding of the construction of NiMH batteries. The major cell features that we captured are six homogenous cores connected to current collectors on each side, current collectors connected in series on top using a circular weld, and cells on each side connected to the external terminals. All the components are encapsulated in a polypropylene case.

The DC resistance of the cell that we used to find the effective resistivity of the core was 15.0 mOhm [5]. We applied a voltage drop of 1.5 volts across the terminals to result a current of 100 A through the cell. Figure 4 shows the voltage distribution and current density in the cores and the welds.

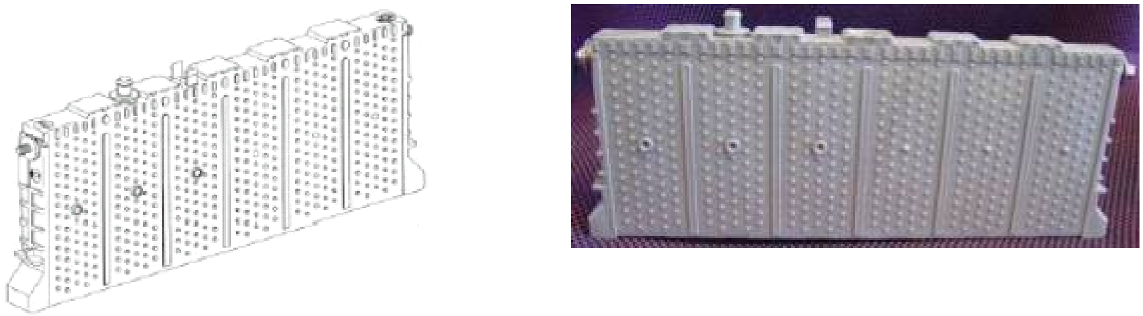


Figure 1: Panasonic NiMH module used in 2001 Toyota Prius

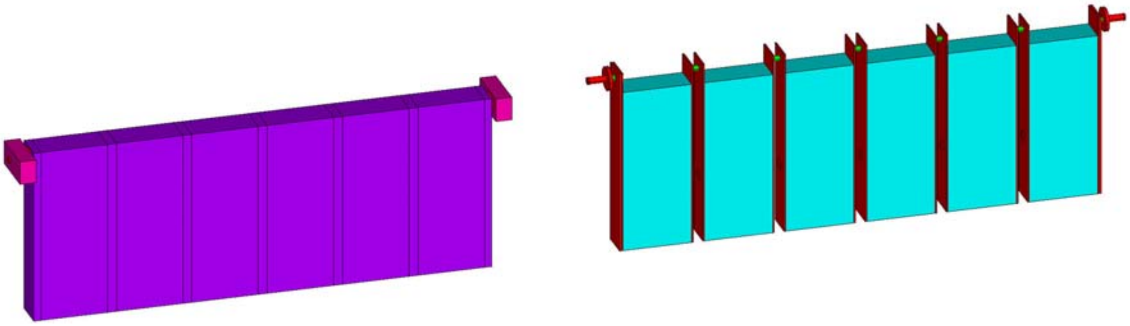


Figure 2: Simulated model of the 2001 Panasonic module. Left: Polypropylene case with terminal connectors. Right: The case is removed to show the core and current collectors.

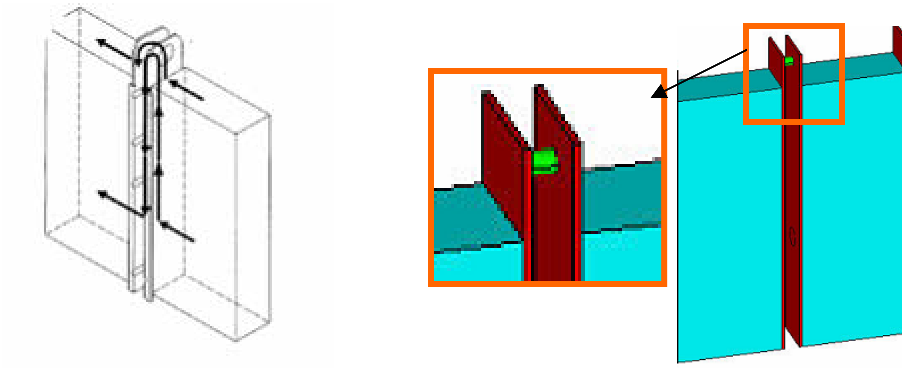


Figure 3: 2001 NiMH module. Left: Schematic of cell-to-cell connections by Panasonic [5]. Right: Our model of the weld junction.

Because the weld junction has the highest current density, and one would expect more heat to be generated in this junction, making it the hottest spot. In fact, Figure 5 shows the transient temperature distribution obtained for a module (with an initial temperature of 28°C) that is being cooled with natural convection while discharging a constant current of 100 A. This simulates a similar case that we tested while capturing infrared thermal images for comparison in our experiments in the laboratory. In Figure 5, the voltage drop across the terminals is 1.5 V, the bottom of the module is insulated, and the heat transfer coefficient on all other sides is set at 5 W/m^2/°C. As seen in Figure 5, the hottest spot does occur at the weld junction of the cell-to-cell interconnects.

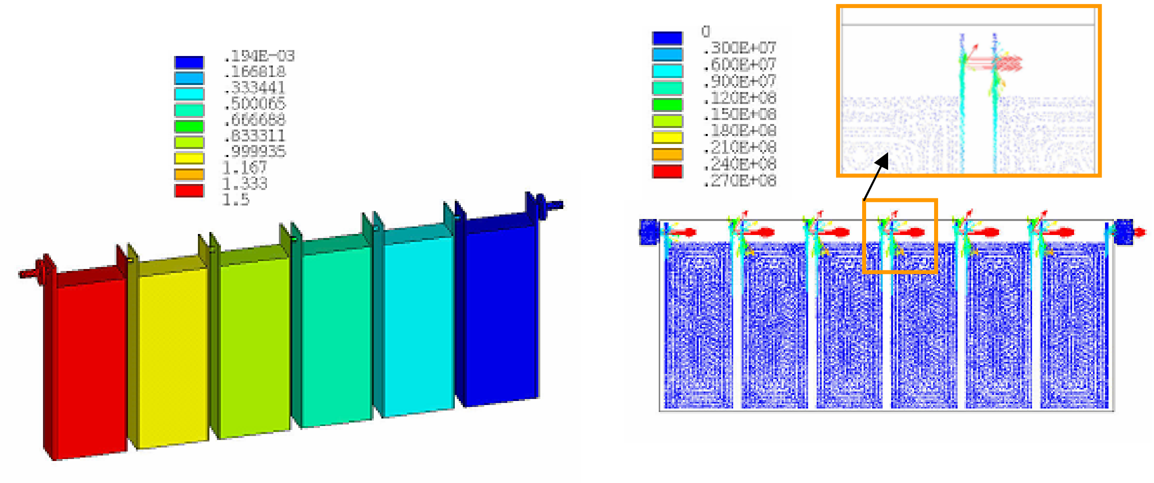
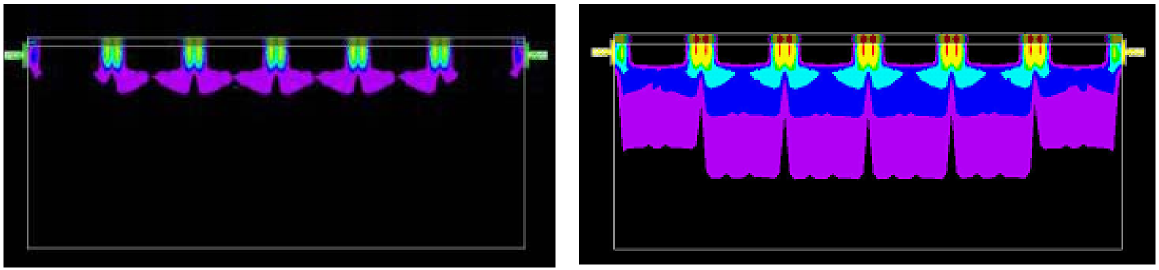
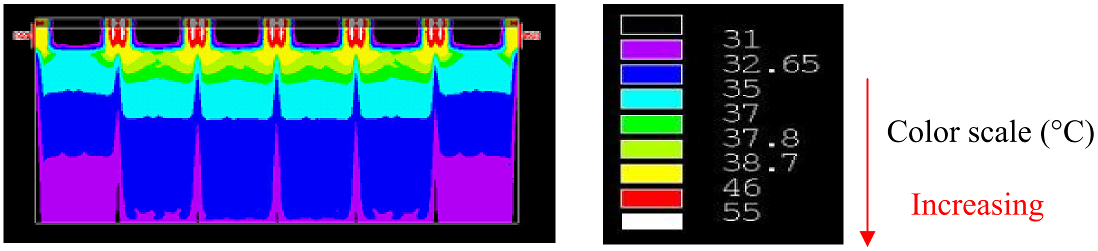


Figure 4: 2001 module. Left: Voltage distribution in each cell. Right: Current density in the module; insert shows the highest current density through the weld junction.



After 2 minutes of discharge

After 2.5 minutes of discharge

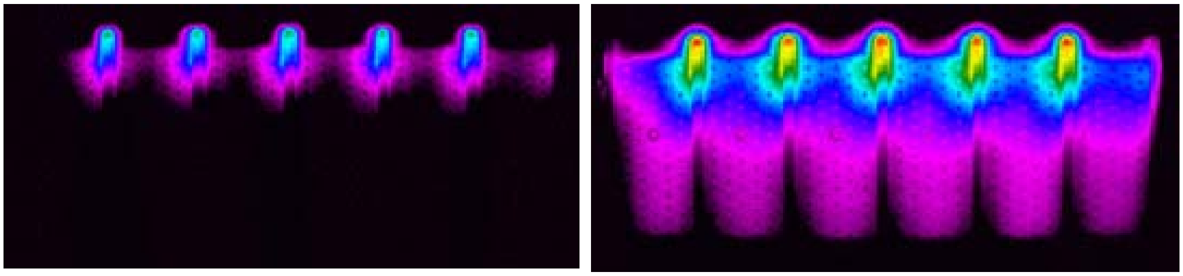


After 3 minutes of discharge

Figure 5: Model predictions for 2001 module. Temperature distribution in the polypropylene case after the start of 100 A discharge.

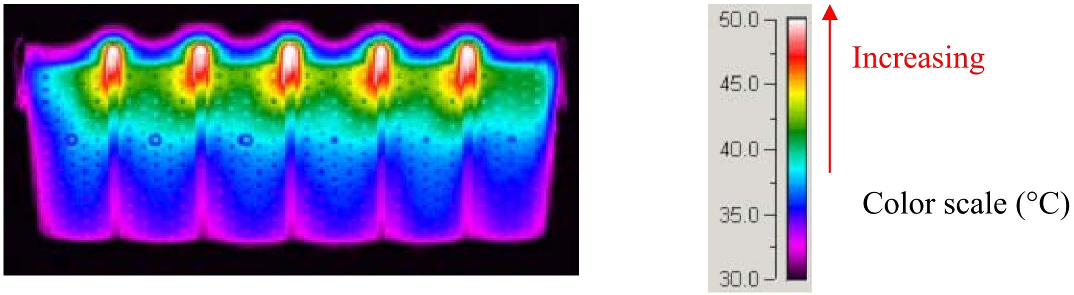
To validate the predictions of the model, or at least its trends, we obtained infrared thermal images of the 2001 Panasonic module under constant current discharge of the 100 A. During this time the module was on a table with no active cooling except for natural convection in the room which was at 25°C to 28°C.

Infrared images show the distribution of the modules external temperature. Figure 6 shows three thermal images of the 2001 module after start of the 100A discharge. The hot spots occur at the weld junctions consistent with the electro-thermal model predictions. Comparing the model predictions in Figure 5 with the experimental images in Figure 6, we conclude that the electro-thermal model predicts the trends of temperature distribution reasonably well.



After 2 minutes of discharge

After 2.5 minutes of discharge



After 3 minutes of discharge

Figure 6: Thermal images of the 2001 NiMH module after the start of 100 A discharge.

Developing the electro-thermal model gives us the ability to find hot spots with a particular design, and propose solutions to eliminate it or reduce its impact. By looking at the thermal images of the 2001 Panasonic NiMH module, we can surmise that reducing the current density at the welds by adding a parallel additional weld junction between current collectors of two adjacent cells would result in reducing the hot spot temperatures. Although this could be difficult or expensive to do, it could improve both thermal and electrical performance of the module. In fact, the engineers at Panasonic have added additional weld junctions between the current collectors of each adjacent cell [5 and 6] for the 2004 generation, as shown in Figure 7. The five new weld junctions are about 2/3 of the way down the module below the top weld. Panasonic indicates that the DC resistance of its 2004 Prismatic NiMH modules has decreased to 11.4 mOhm, thus its power capability has gone up by 30% to 1300 W/kg, while its ampere-hour capacity remains the same [5 and 6].

Figure 7 shows the finite element model of the 2004 Panasonic NiMH module. The weld junctions were simulated as small cylindrical rods connecting adjacent cells. Figure 8 shows the model prediction for current density in the 2004 NiMH module under 100A discharge. As seen, the current density is less in the top welds when compared to the 2001 module under the same 100A discharge (Figure 4). Now the current flow is split more or less in half between the top and middle welds. With lower current density in the welds, less heat gets generated, thus temperature increase at the welds is expected to be less.

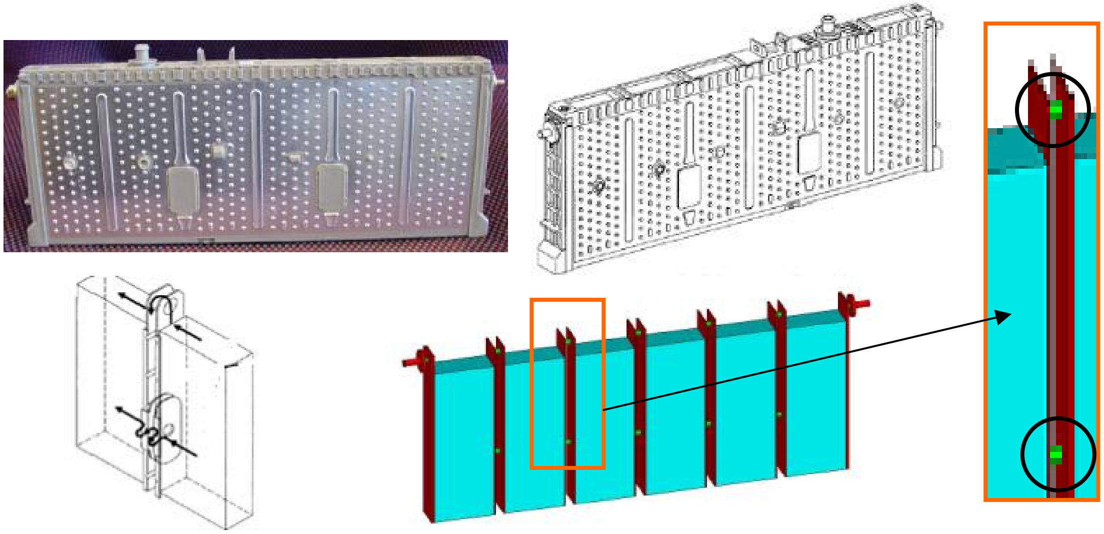


Figure 7: New Panasonic NiMH Module used in 2004 Toyota Prius (top picture and schematic; schematic of cell-to-cell connections by Panasonic [5] (bottom left); our simulated model of the module and weld junction (colored images on the right)

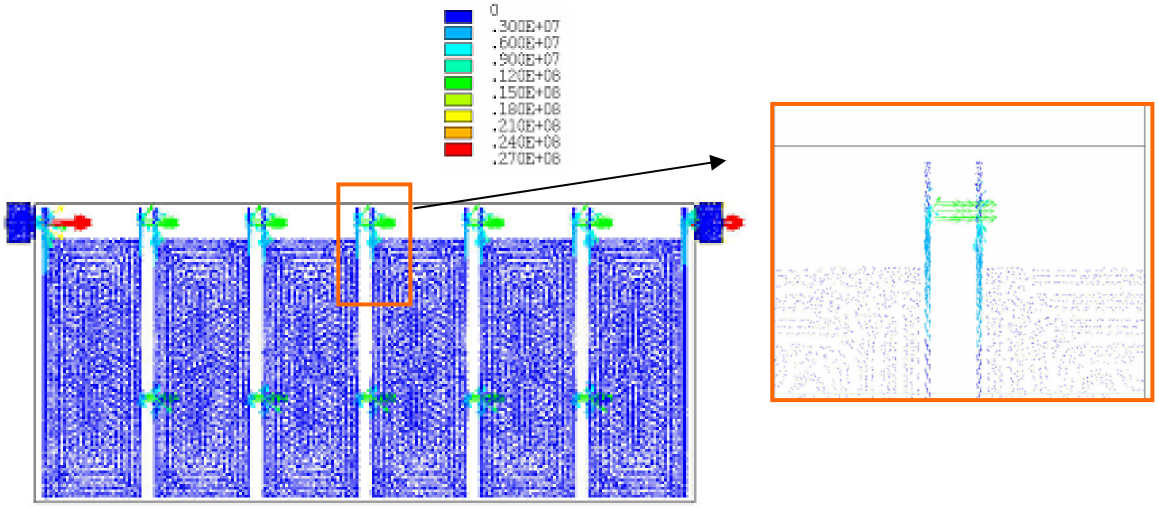


Figure 8: Current density for 100 A discharge for 2004 NiMH module

Figure 9 shows the temperature distribution in the 2004 module at the end of three minutes of discharge. The left image shows the polypropylene case temperature. The right image shows the core, current collector, and cell-to-cell interconnects. By comparing these results with the similar case in Figure 5, we can see that the overall temperature of the 2004 module is lower than that of the 2001 module (maximum of 48°C vs maximum of 55°C). In addition, the 2004 module has a much better uniformity in temperature. both of these would help increase the overall performance and reliability of the battery.

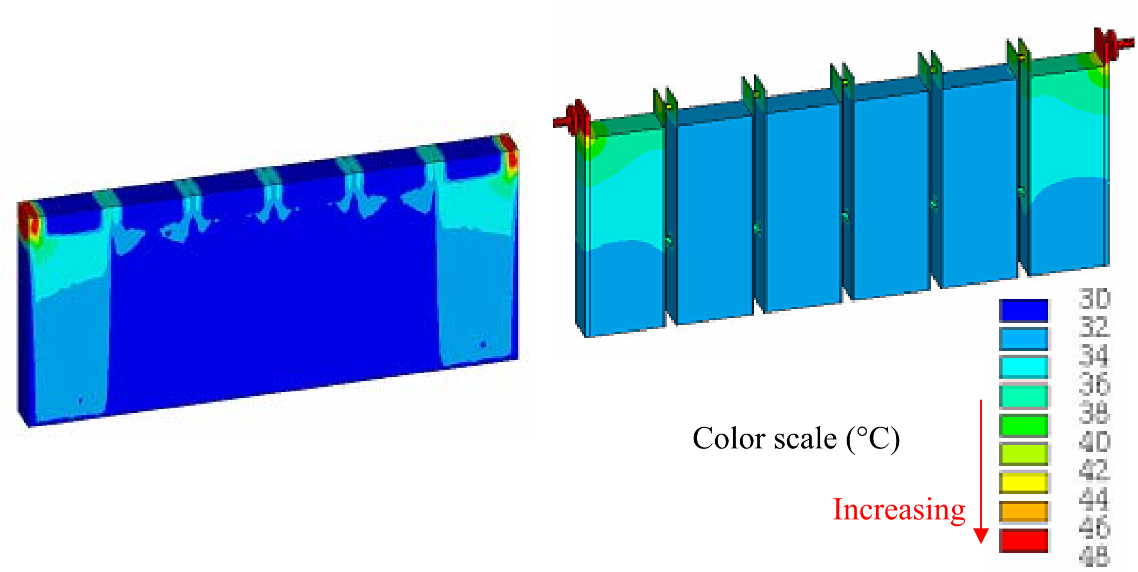


Figure 9: Model predictions for 2004 module. Temperature distribution in the case (left) and in the core (right) after 3 minutes from the start of 100 A discharge.

Figure 10 shows the thermal image of the 2004 NiMH module under 100A discharge. Unlike the 2001 module (shown in Figure 6), it does not have any hot spots at the top cell-to-cell interconnects. It does have lower overall temperature and a more even temperature distribution. Our electrochemical model predictions compare well with these observations and experimental thermal images.

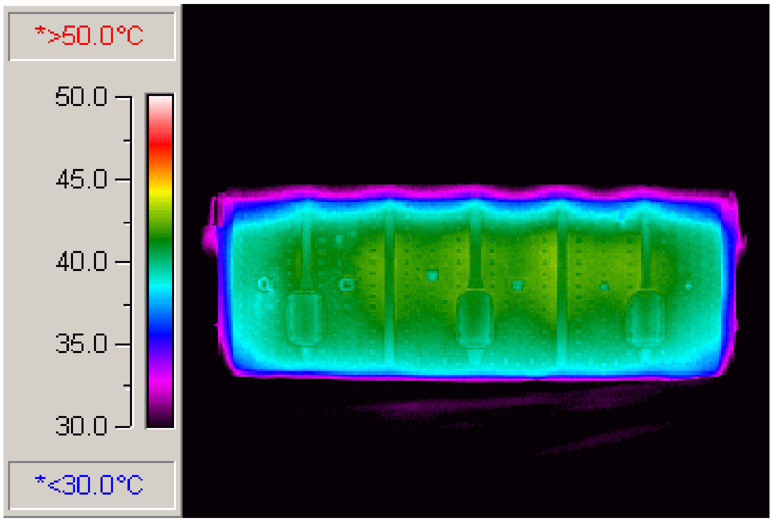


Figure 10: Thermal image of the 2004 NiMH module 3 minutes after the start of 100 A discharge.

4 Concluding Remarks

Thermal control is critical to ensure batteries provide the desired electrical performance and long life. Good thermal performance starts with designing good cells and modules. Using commercial finite element analysis software, we have captured both electrical and thermal behavior of cells and modules with all of the geometrical details. To illustrate how the electro-thermal modeling works, we applied it to the 2001 Prismatic Panasonic NIMH module and discovered hot spots near cell-to-cell interconnects. The analysis showed the benefit of decreasing the overall DC contact resistance between the two adjacent cells by using additional welds to reduce hot spots, improve temperature uniformity, and reduce the overall temperature of the module. This is consistent with what Panasonic has accomplished in their 2004 module.

We performed constant current discharges of the 2001 and 2004 modules and obtained thermal images. Comparing the thermal images with model predictions indicated that the model predicts the thermal performance reasonably well. We have since applied this electro-thermal process to two other cell and battery designs for the Department of Energy's FreedomCAR battery developers to help them improve thermal designs.

The current version of the electro-thermal model does not capture the transient nature of the internal resistance of the battery due to electrochemical changes in the battery as it charges or discharges. It also does not capture the chemical behavior of the various materials in the cells. We plan to update and upgrade the model to include such features. Including the chemical behavior of the materials in the cells may allow us to predict the cells thermal performance and the heat propagation to other cells in module under abuse conditions (overcharge, overheating, and short-circuit).

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