Battery Thermal Characterization

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Project ID # ES204

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Overview

Timeline

- **Project Start Date: 10/2004**
- **Project End Date: 9/2018**
- **Percent Complete: Ongoing**

(Supporting ongoing DOE/USABC battery developments)

Budget

- **Total Project Funding:**
  - DOE Share: 100%
  - Contractor Share: 0%
- **Funding Received in FY15: $500K**
- **Funding for FY16: $500K**

Barriers

- Decreased battery **life** at high temperatures.
- High **cost** due to an oversized thermal management system.
- Cost, size, **complexity,** and energy consumption of thermal management system.
- Decreased **performance** at low temperatures.
- Insufficient cycle life stability to achieve the 3,000 to 5,000 “charge-depleting” deep discharge cycles.

Partners

- USABC – GM, Ford, Fiat-Chrysler (FCA)
- JCI
- Leyden
- LGCPI
- Maxwell
- Saft
- SK Innovation
- Seeo

Relevance of Battery Thermal Testing and Modeling

Life, cost, performance, and safety of energy storage systems are strongly impacted by ***temperature***

as supported by testimonials from leading automotive battery engineers, scientists, and executives.

Objectives of NREL's work

- To thermally characterize cell and battery hardware and provide technical assistance and modeling support to DOE/U.S. DRIVE, USABC, and battery developers for improved designs.
- To enhance and validate physics-based models to support the thermal design of long-life, low-cost energy storage systems.
- To quantify the impacts of temperature and duty cycle on energy storage system life and cost.

USABC = U.S. Advanced Battery Consortium
U.S. DRIVE - United States Driving Research and Innovation for Vehicle Efficiency and Energy

Milestones

Month/ Year	Milestone or Go/No-Go Decision	Description	Status
9/2015	Milestone	Report on thermal evaluation of advanced cells and battery packs	Complete
12/2015	Milestone	Present thermal data at USABC technical review meetings	Complete
3/2016	Milestone	Report on battery thermal data for USABC cells	Complete
6/2016	Milestone	Present thermal data at USABC technical review meetings	On Track
9/2016	Milestone	Report on battery thermal data of USABC battery cells/packs	On Track

Thermal Testing – Approach

Cells, Modules, and Packs

Tools
- Calorimeters
- Thermal imaging
- Electrical cyclers
- Environmental chambers
- Dynamometer
- Vehicle simulation
- Thermal analysis tools

Test Profiles
- Normal operation
- Aggressive operation
- Driving cycles
  - US06
  - UDDS
  - HWFET
- Discharge/charge rates
  - Constant current (CC)
  - Geometric charge/discharge
  - FreedomCAR profiles

Measurements
- Heat capacity
- Heat generation
- Efficiency
- Thermal performance
  - Spatial temperature distribution
  - Cell-to-cell temperature imbalance
  - Cooling system effectiveness

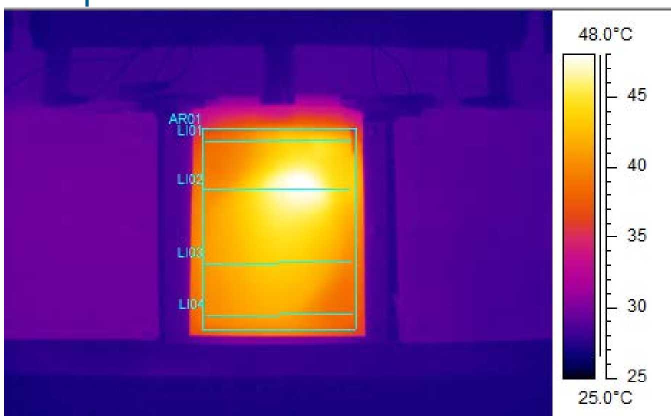
- **NREL provides critical thermal data to the battery manufacturers and OEMs that can be used to improve the design of the cell, module, and pack and their respective thermal management systems.**
- **The provided data include infrared imaging results and heat generation of cells under typical profiles for HEV, PHEV, and EV applications.**

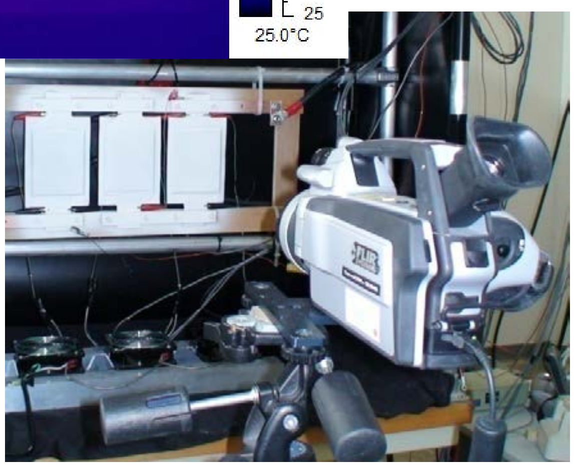
EV = electric vehicle; HEV = hybrid electric vehicle; OEM = original equipment manufacturer; PHEV = plug-in hybrid electric vehicle; HWFET = Highway Fuel Economy Test; UDDS = Urban Dynamometer Driving Schedule

Thermal Testing – Approach

Thermal Imaging

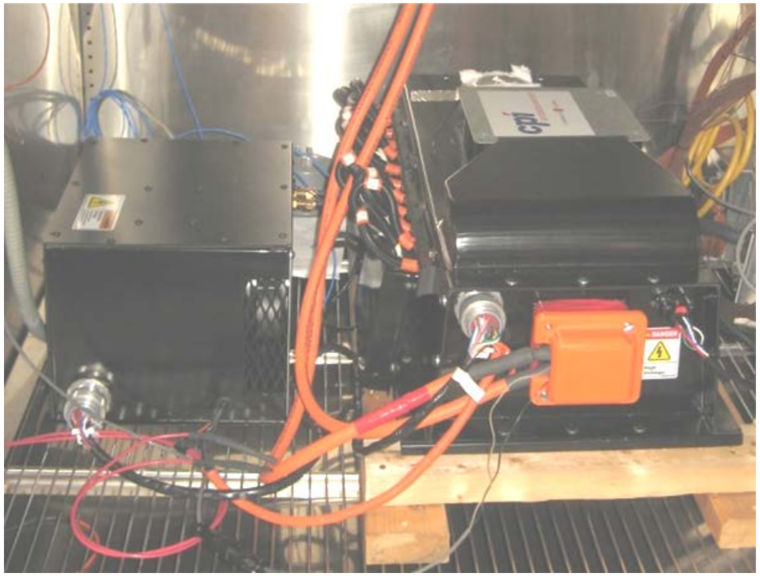
- **Temperature variation** across cell
- Profiles: US06 cycles, CC discharge/charge
- Unique testing method reducing environmental impacts





Thermal Management Performance

- **Temperature variation** across pack under realistic conditions
- Assessing vapor compression, air, and liquid cooling systems
- Profiles: US06 cycles, CC discharge/charge



- Results reported to DOE, USABC, and battery developers

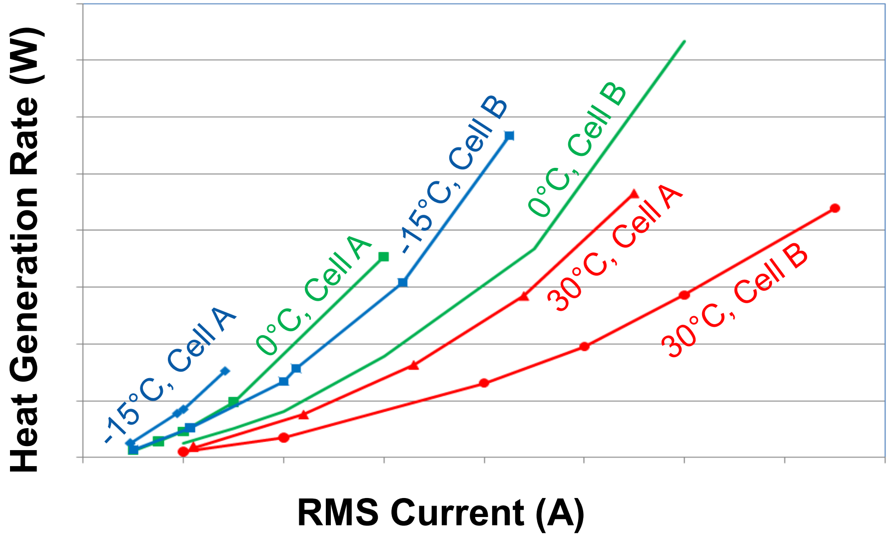
Photos by Kandler Smith, NREL

Heat Generation and Efficiency – Approach

Using state-of-the-art isothermal battery calorimeters

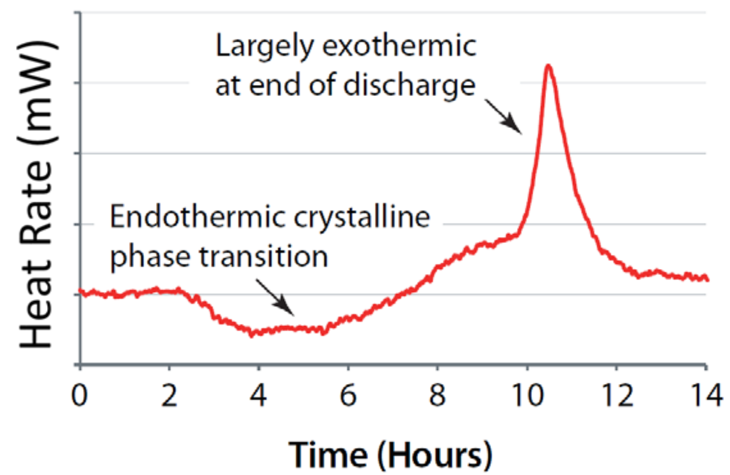
Top view of large calorimeter test chamber

Photo by Dennis Schroeder, NREL



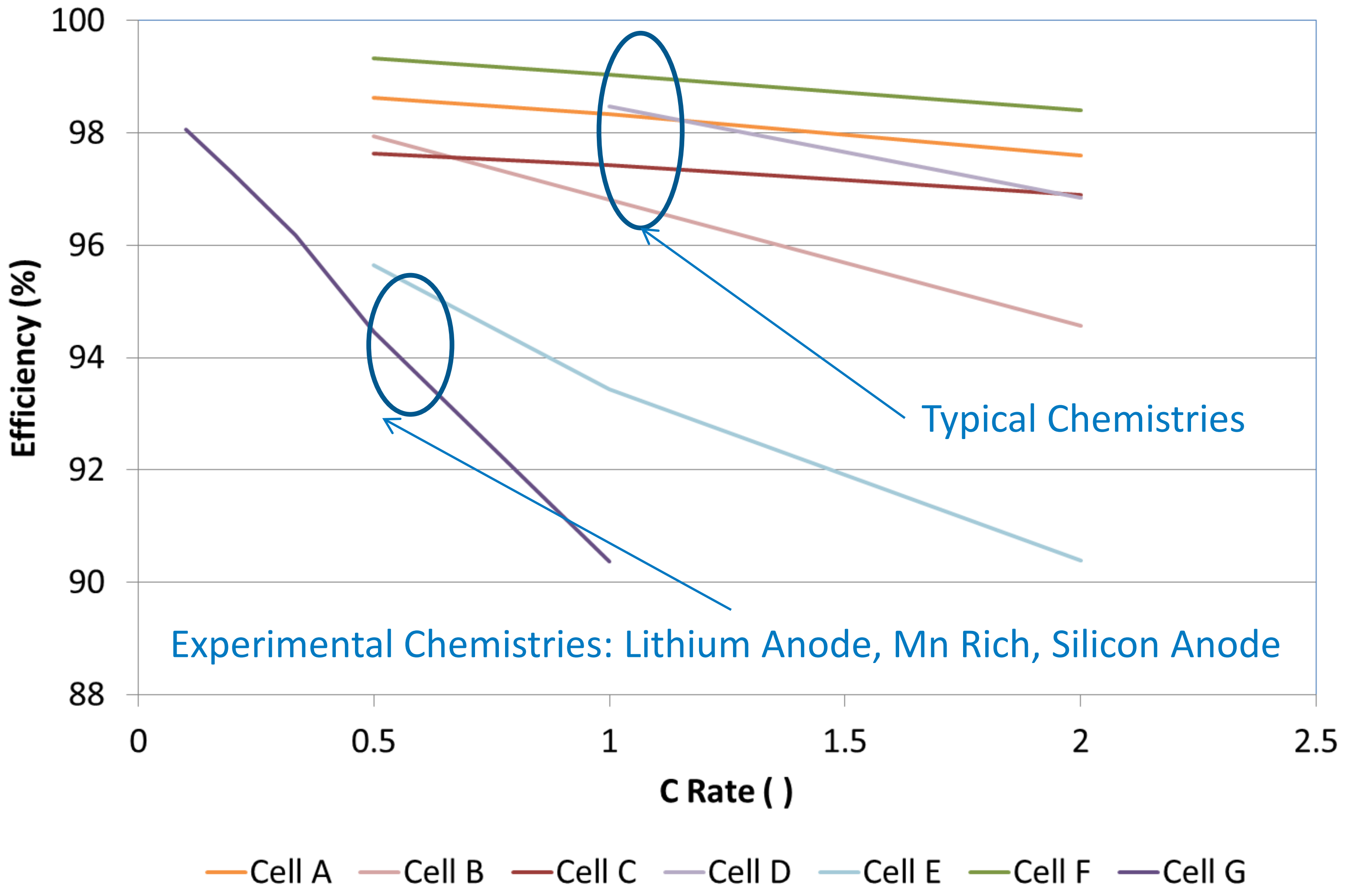
- **Heat generation**, heat capacity**,** and efficiency
- Test temperature range: -30°C to +45°C
- Profiles: USABC and US06 cycles, CC

Specifications	Cell Calorimeter	Module Calorimeter	Pack Calorimeter
Maximum Voltage (Volts)	50	500	600
Sustained Maximum Current (Amps)	250	250	450
Excursion Currents (Amps)	300	300	1000
Volume (liters)	9.4	14.7	96
Maximum Dimensions (cm)	30.5 x 20.3 x 15.2	35 x 21 x 20	60 x 40 x 40
Operating Temperature (ºC)	-30 to 60	-30 to 60	-40 to 100
Accuracy at Minimum Heat (%)	2	2	2
Maximum Constant Heat Generation (W)	50	150	4000



Efficiency Comparison of Cells Tested in FY15 and FY16 at 30°C Under Full Discharge from 100% to 0% SOC

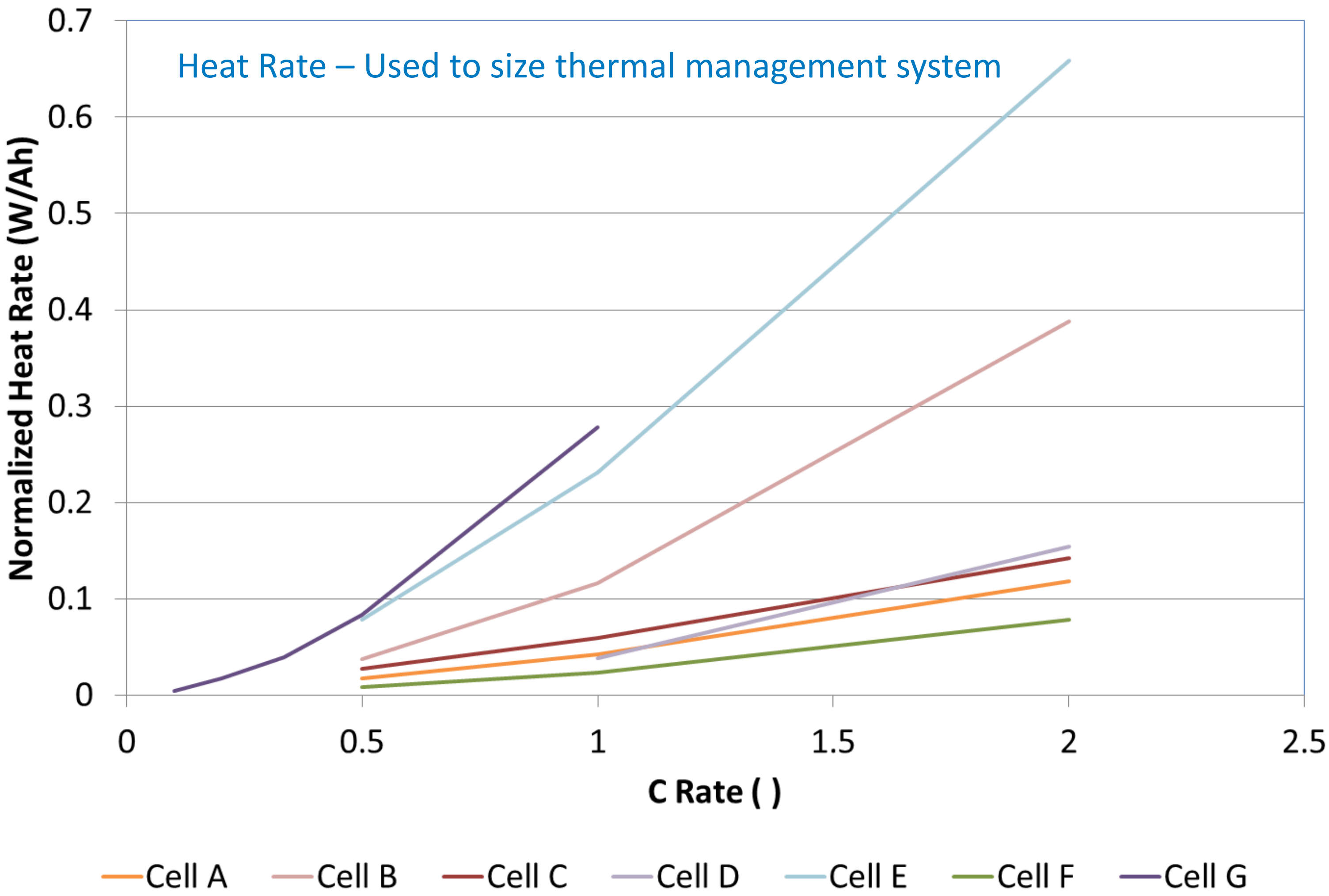
Technical Lessons Learned



SOC – state of charge

Heat Rate Comparison of Cells Tested in FY15 and FY16 at 30°C Under Full Discharge from 100% to 0% SOC

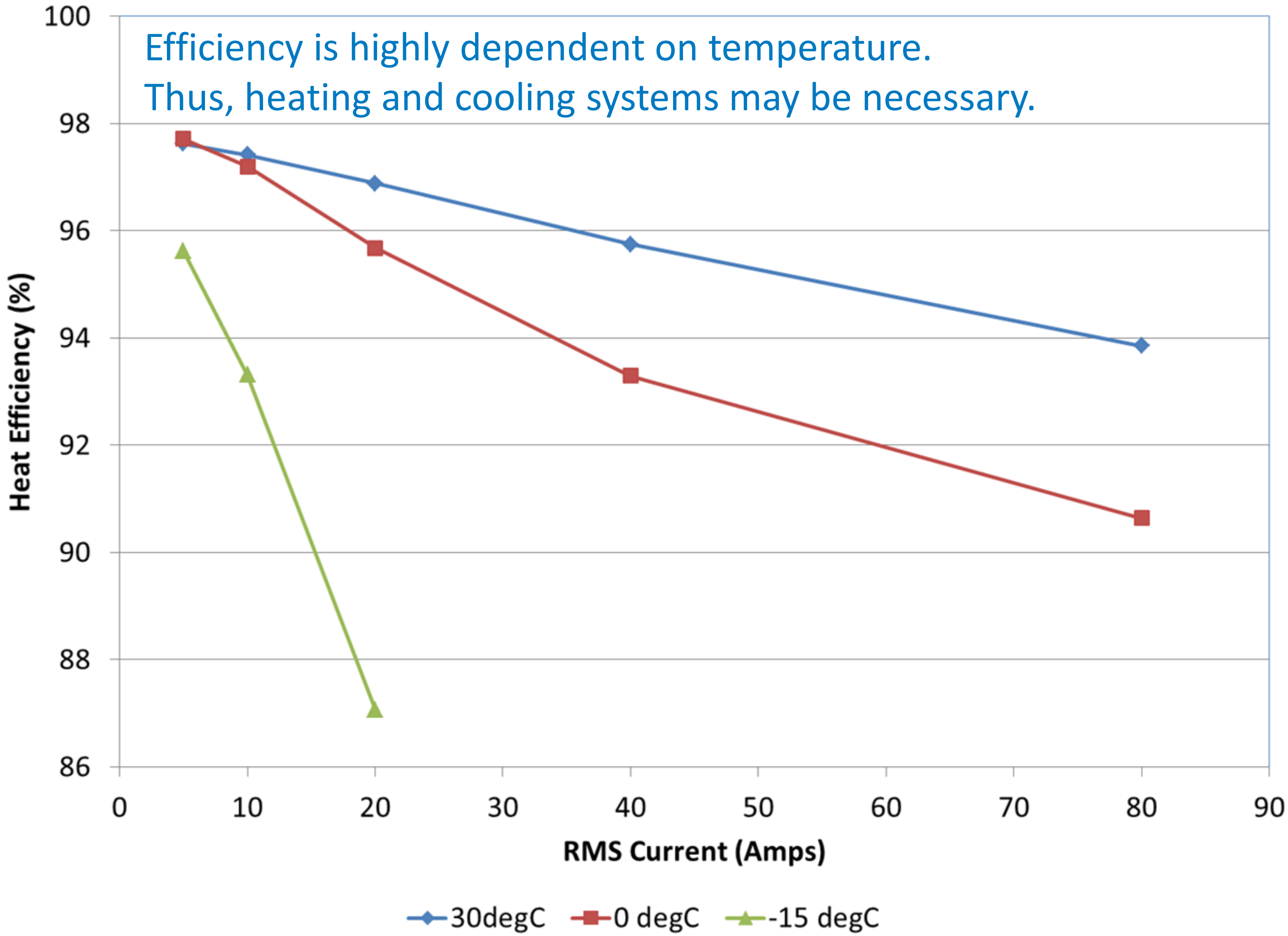
Technical Lessons Learned



SOC – state of charge

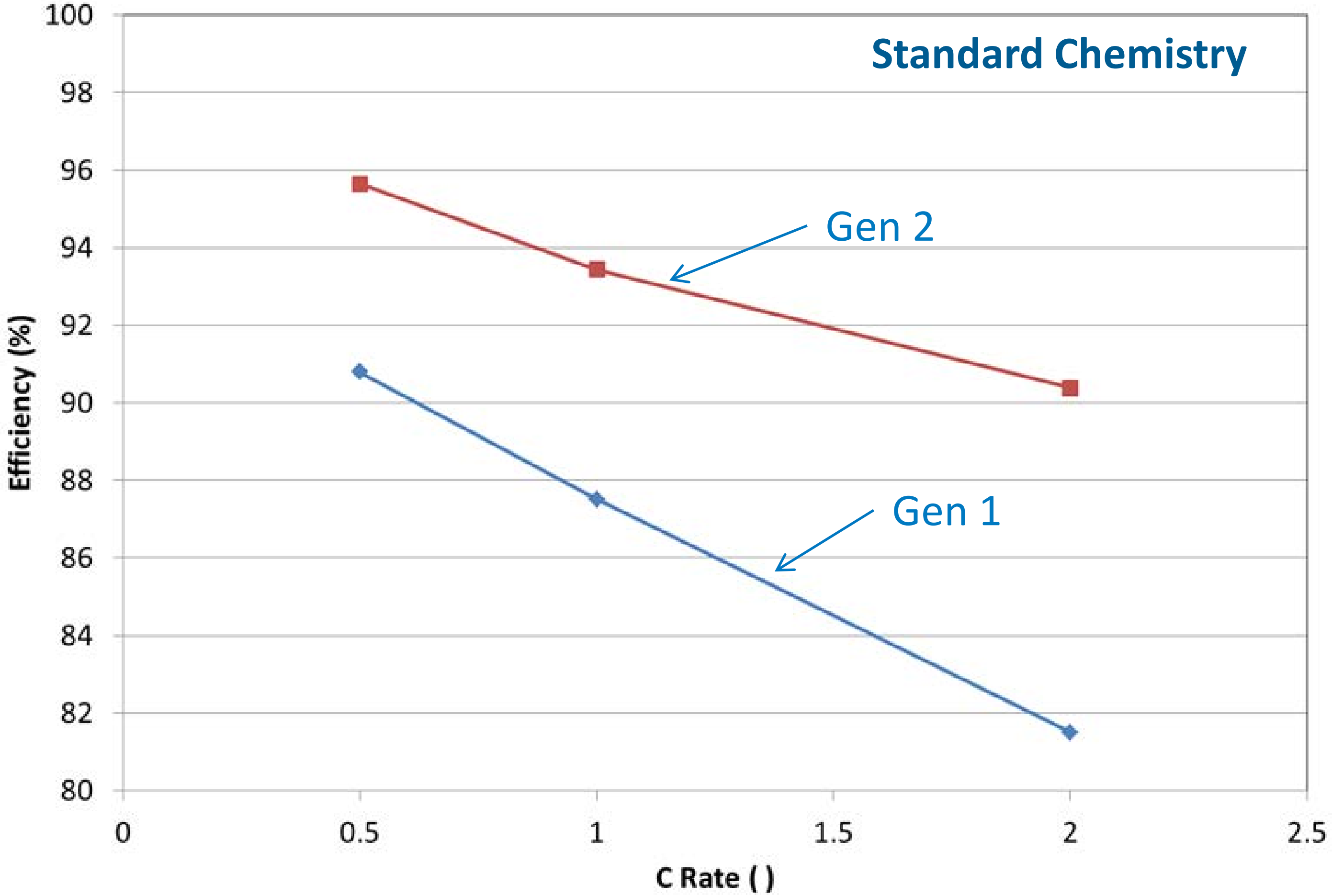
Lithium Cell Efficiency at 30°C, 0°C, and -15°C Under Full Discharge from 100% to 0% SOC

Technical Lessons Learned



EV Cell Gen1/Gen 2 Efficiency Comparison

Technical Lessons Learned



During the USABC programs, electrochemical and mechanical design changes are made to the cells. Calorimetry can determine if the changes are positive.

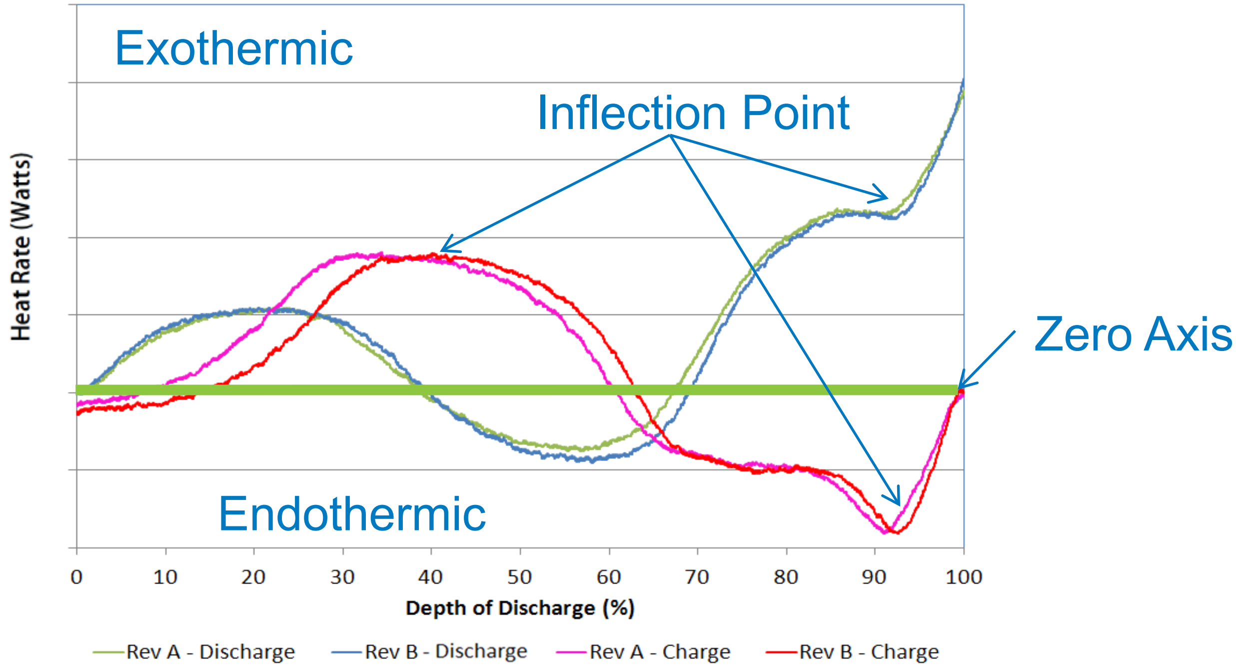
Low-Current Entropic Heating

Technical Lessons Learned

Heat in a cell is produced by:

- The resistance of the various cell components (electrode, cathode, anode, etc.); this is known as Joule heating, which can be minimized by cycling the cells at low currents
- Entropic reactions within the cell—exothermic and endothermic reactions within the cell due to the transfer of ions and electrons.

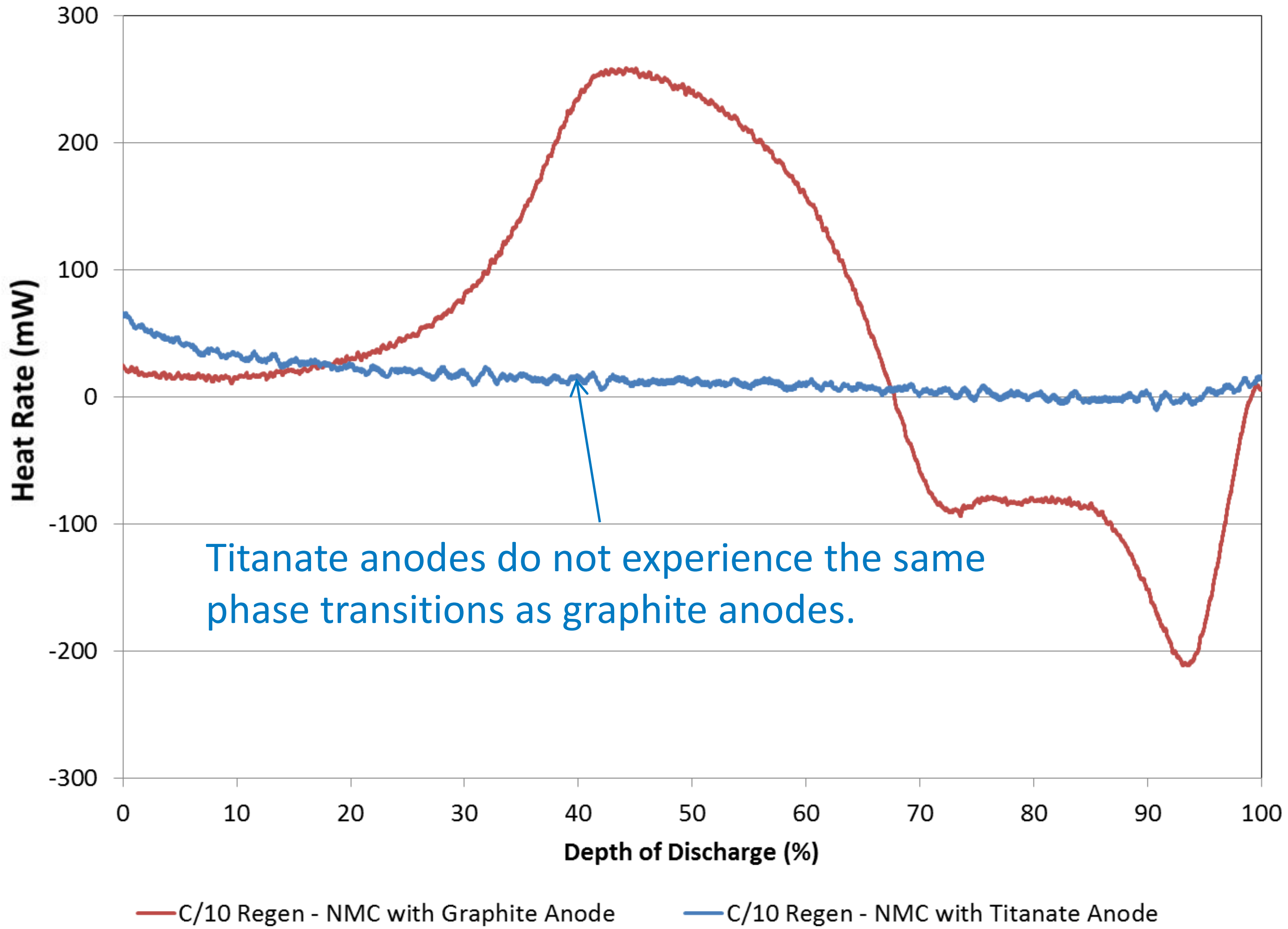
Cycling the battery at the inflection points may cause cracks in the anode or cathode, which may lead to decreased performance and life.



In general, Joule heating is an order of magnitude less than the entropic heating.

Titanate Anodes Limit Phase Transition

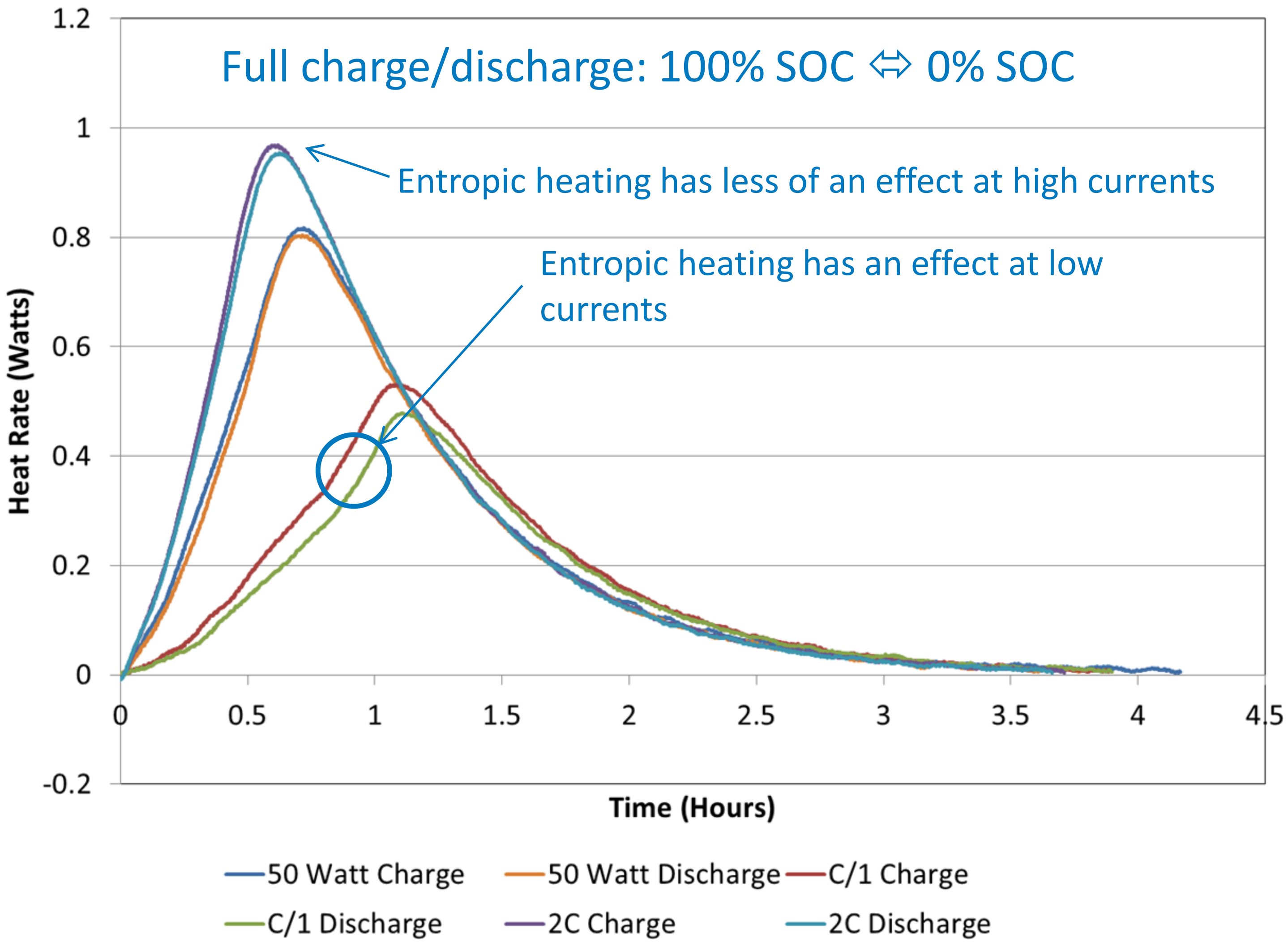
Technical Lessons Learned



NMC = nickel manganese cobalt

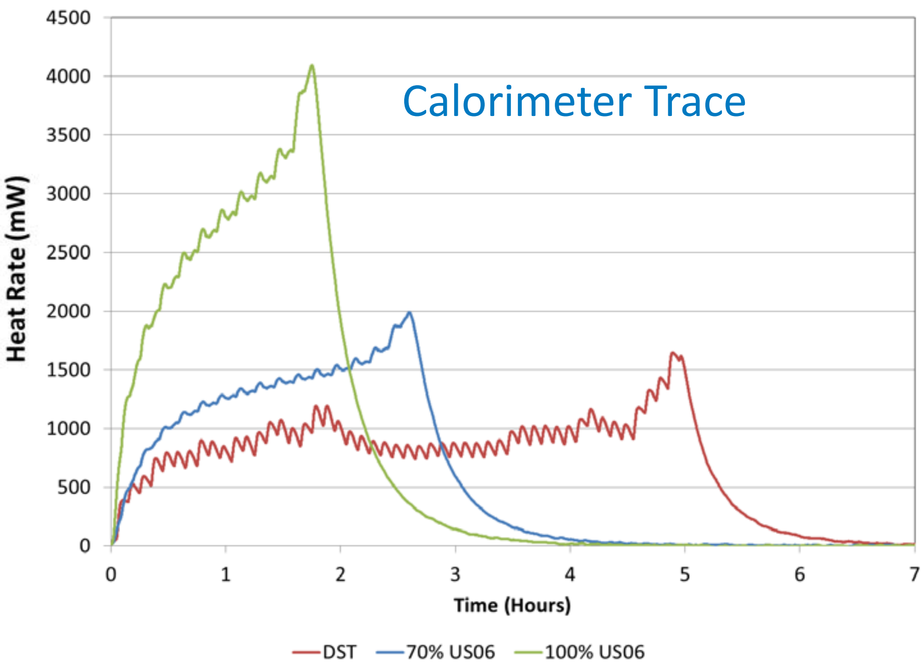
Calorimetry Testing Can Identify Entropic Heating/Cooling

Technical Lessons Learned



Heat Generation under Various Drive Cycles

Technical Lessons Learned



Calorimeter can measure the efficiency and heat generation under various drive cycles—helps in designing thermal management systems for battery packs.

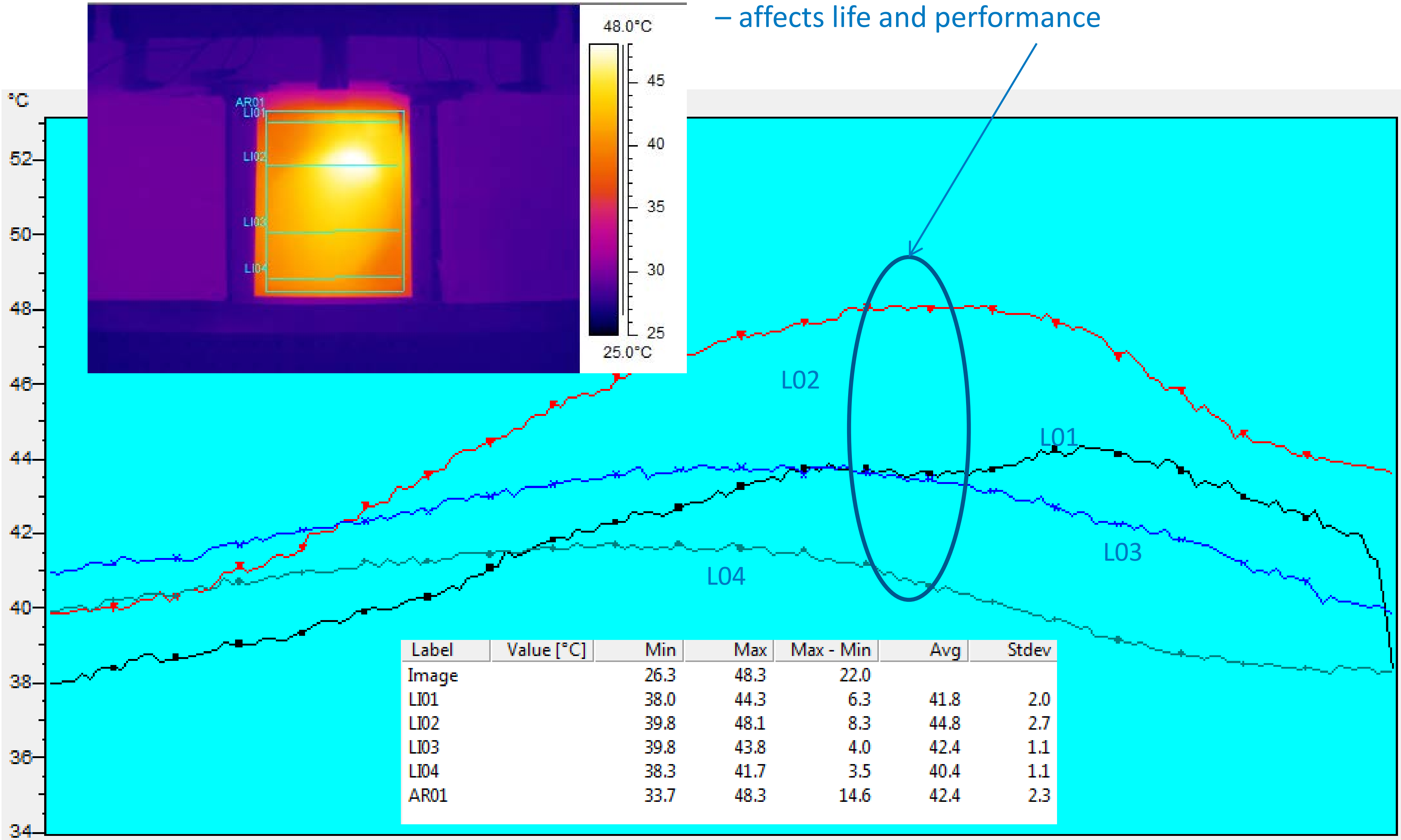
Cycle type can have a large effect on efficiency and heat rate.

Cycle	RMS Current (amps)	Efficiency (%)	Heat Rate (watts/cell)
DST	4.9	95.3	0.5
70% Power USO6	8.0	93.9	1.2
100% Power US06	11.8	91.1	2.6

PHEV/EV Cell at End of 2C Constant Current Discharge

Technical Lessons Learned

Large temperature variations across surface of cell – affects life and performance



Label	Value [°C]	Min	Max	Max - Min	Avg	Stdev
Image		26.3	48.3	22.0		
LI01		38.0	44.3	6.3	41.8	2.0
LI02		39.8	48.1	8.3	44.8	2.7
LI03		39.8	43.8	4.0	42.4	1.1
LI04		38.3	41.7	3.5	40.4	1.1
AR01		33.7	48.3	14.6	42.4	2.3

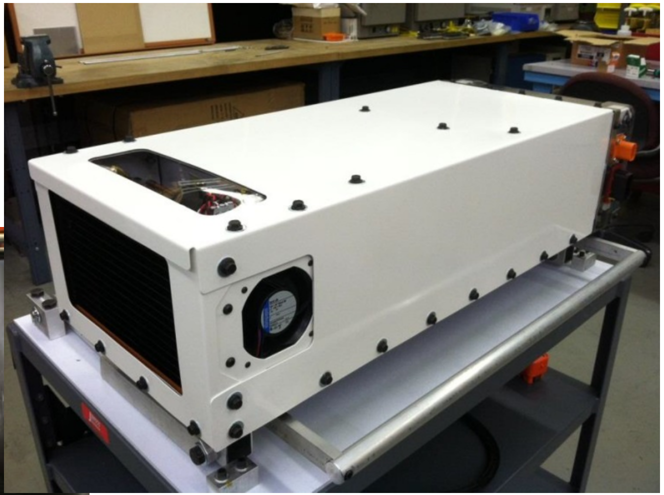
Pack Thermal Temperature Studies

Technical Lessons Learned

Measured temperature rise, temperature uniformity, and parasitic losses versus temperature and duty cycle, extrapolating calendar life for different scenarios with and without active cooling.

A123

JCS

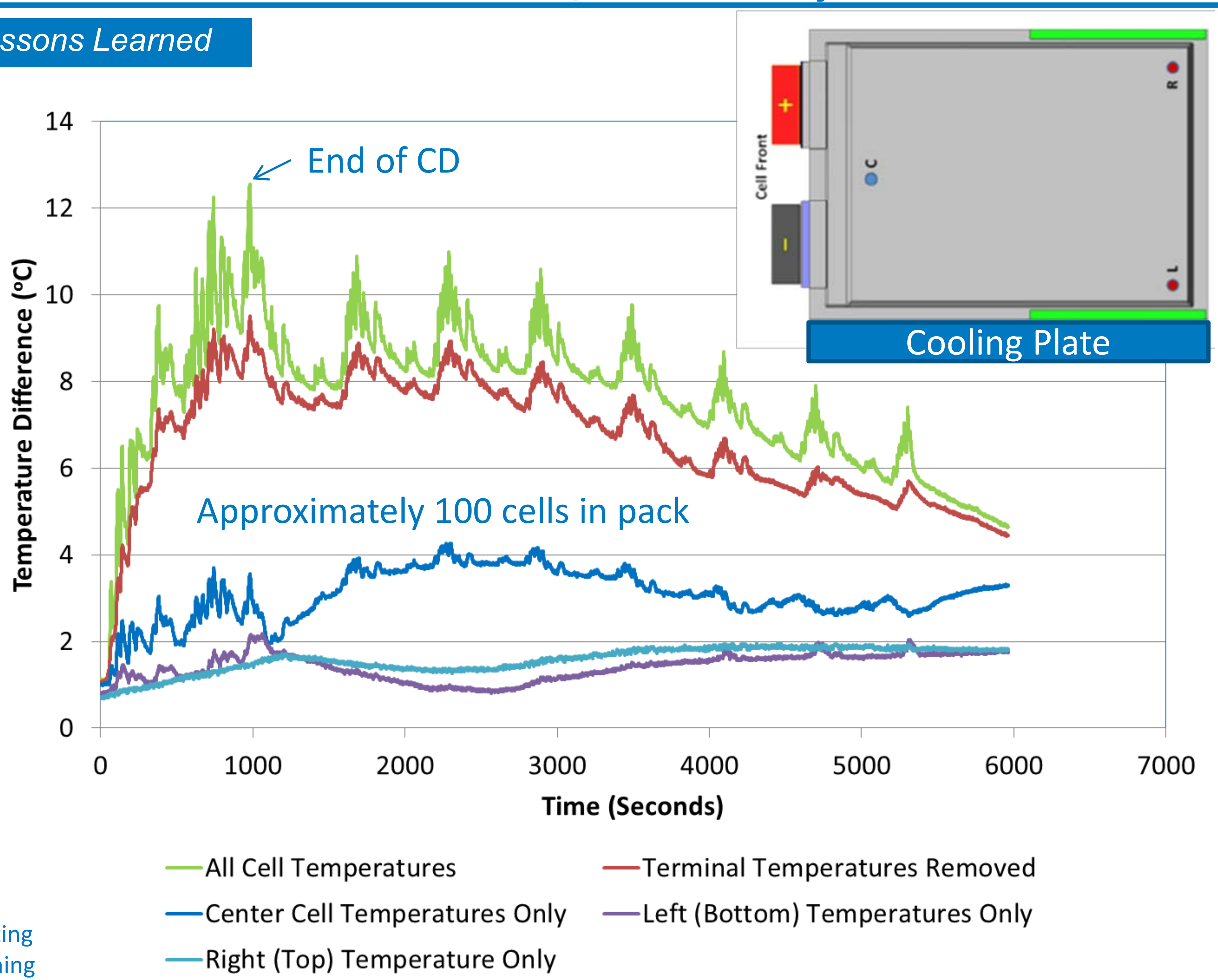


LGCPI

Photos by Dirk Long, NREL

Thermal Management System Performance Under a PHEV CD/CS Drive Cycle

Technical Lessons Learned



CD = charge depleting
CS = charge sustaining

Thermal Management System Performance Under a PHEV CD/CS Drive Cycle

Technical Lessons Learned

		End of CD Cycle		End of CS Cycle	
Test	**Ambient Temp. (^oC)**	**Maximum Temp. (^oC)**	**Delta Temp. (^oC)**	**Maximum Temp. (^oC)**	**Delta Temp. (^oC)**
US06 PHEV CDCS	30	45	12.1	29	8.4
US06 PHEV CDCS	40	52	12.2	30	9.7

- **The recent U.S. DRIVE RFPI limits the cell-to-cell temperature in a PHEV pack to less than 3^{o}C. In this pack the cell-to-cell temperature difference is greater than 12^{o}C.**
- **If not properly designed, thermal management systems can cause a large cell-to-cell temperature spread. These temperature differences affect the cycle life of each cell, potentially resulting in warranty issues.**

Responses to Previous Year Reviewers' Comments

Reviewer Comment: The reviewer found the entropic studies quite interesting to learn about, but was unsure how that will lead to improvements in design. The reviewer also noted that publications in peer-reviewed literature were not included in the list of accomplishments, asking if this was not important for the project.

Presenter Response: The entropic studies give an indication of where the battery can be cycled to avoid mechanically fracturing the cathode and anode. When a cell is cycled from 100% to 0% SOC, the cathode and anode material can go through several morphology changes. The changes will coincide with the contraction/ expansion of the active material. To limit the mechanical stress on the active material, the battery manufacturer or end user can choose to limit the amount of time at these phase transition points, thereby extending the life of the battery. NREL's calorimeters will indicate where these phase transitions occur.

As for peer-reviewed publications, we are required to keep the information generated under this task confidential/proprietary for a period of 5 years. This requirement limits our ability to publish in peer-reviewed journals.

Responses to Previous Year Reviewers' Comments

Reviewer Comment: While several partners were listed, the reviewer noted, it was not clear how the PIs are working with those partners. For example, the reviewer said, it was unclear if the PIs are testing batteries from all or some of the partners.

Presenter Response: We work with USABC/U.S. DRIVE (GM, Ford, FCA) to identify promising battery technologies and then engage the manufacturers to develop these technologies for HEV, PHEV, and battery EV applications. Other than U.S. DRIVE, we have worked and tested the battery technologies for each of the other partners listed in the presentation and poster. We typically present our results each quarter to the battery manufacturers and show how their technology can be effectively utilized and/or improved to meet the goals for the specific program.

Collaborators

- **USABC partners Fiat-Chrysler (FCA), GM, and Ford**
- **USABC Contractors – Technology Evaluated at NREL**
    - JCI
    - Leyden
    - LGCPI
    - Maxwell
    - Saft
    - SK Innovation
    - Seeo

Remaining Challenges and Barriers

- Address life issues at high and low temperatures—15-year target.
- Address high energy storage <u>cost</u> due to battery packaging and integration costs.
- Reduce the cost, size, complexity, and energy consumption of <u>thermal management</u> systems.
- Optimize the design of passive/active thermal management systems—explore new cooling strategies to extend the life of the battery pack.

Proposed Future Work

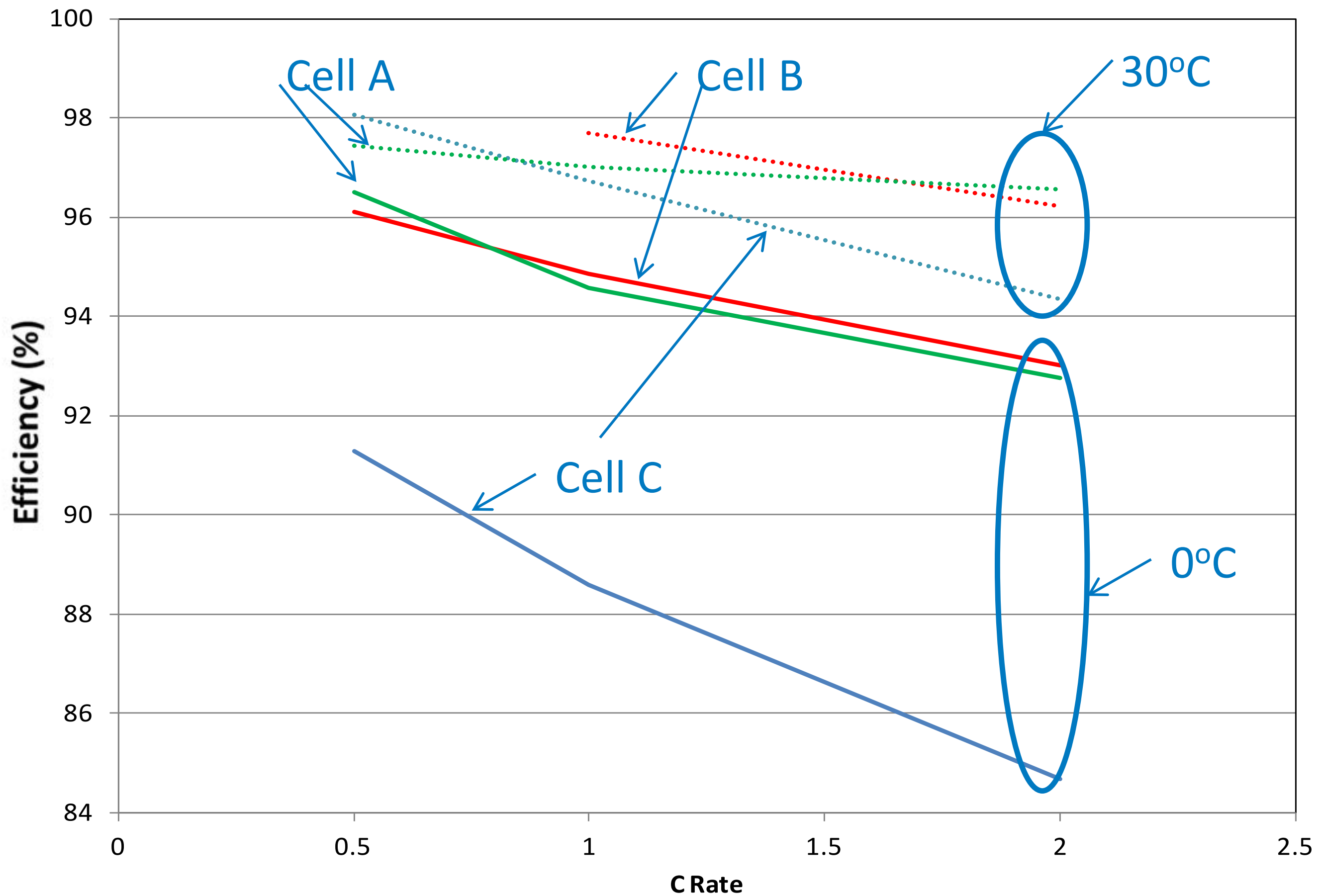
- **Continue thermal characterization for DOE, USABC, and partners**
    - Cell, module, and subpack calorimeters are available for industry validation of their energy storage systems.
- **Develop battery usage models with the calorimeter heat generation data that will predict the thermal performance of energy storage systems under various drive cycles and environmental conditions—models to be utilized by GM, Ford, Fiat-Chrysler (FCA), and battery developer(s).**
- **The data will be used to enhance physics-based battery models in conjunction with DOE's Computer-Aided Engineering for Automotive Batteries (CAEBAT) program.**
- **Continue to develop and evaluate liquid, air, and vapor compression thermal management systems to extend the energy storage cycle life.**
- **Work with OEMs and battery manufacturers to identify:**
    - The best solutions to reduce the cell-to-cell temperature variations within a pack in order to extend life.
    - Minimize parasitic power draws due to the thermal management system.
    - Investigate new solutions for the thermal management of batteries – phase change material, new refrigerants, etc.

Summary

- **We collaborated with U.S. DRIVE and USABC battery developers to obtain thermal properties of their batteries.**
  - We obtained heat capacity and heat generation of cells under various power profiles.
  - We obtained thermal images of the cells under various drive cycles.
  - We used the measured results to validate our thermal models.
  - All the data have been shared with the battery developers.
- **Thermal properties are used for the thermal analysis and design of improved battery thermal management systems to support and achieve life and performance targets.**

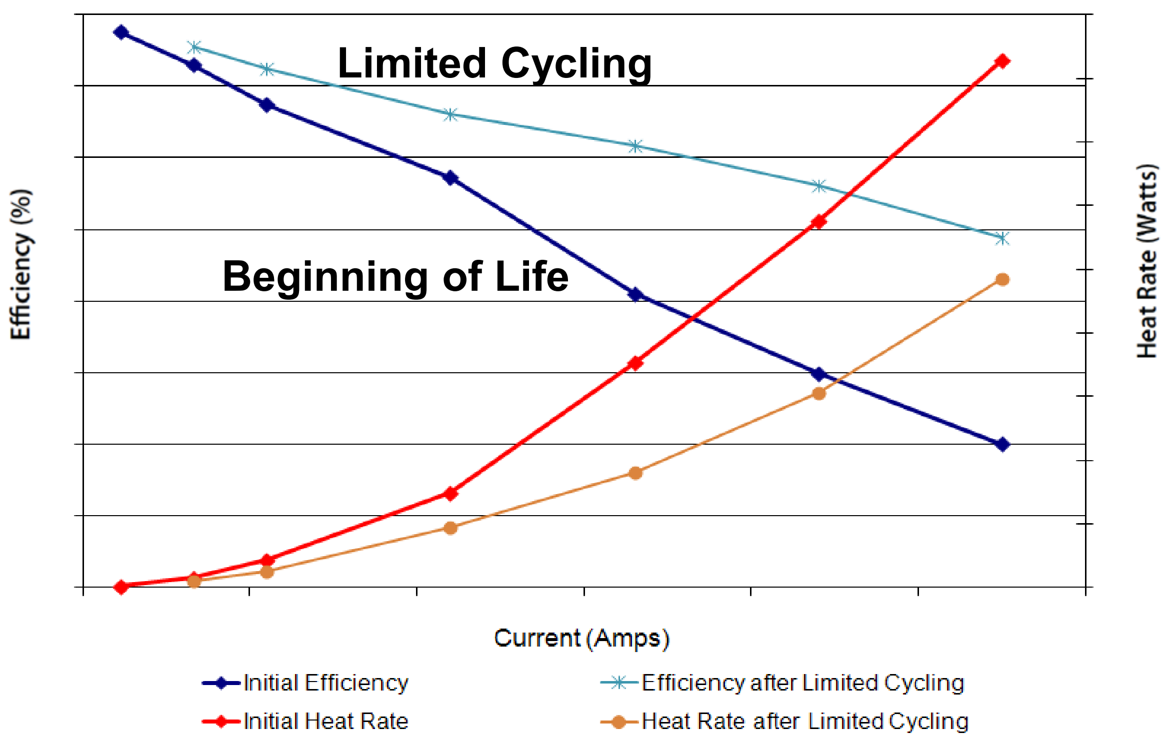
Technical Back-Up Slides

Efficiency Comparison of Cells Tested at 30°C and 0°C under Full Discharge from 100% to 0% SOC



Testing the efficiency of cells at multiple temperatures shows how different additives/designs will affect performance.

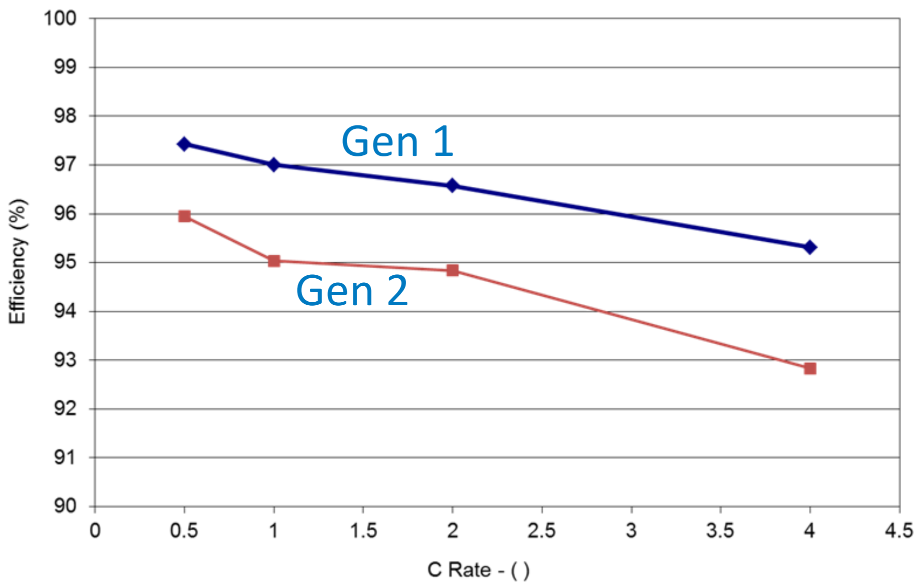
Efficiency Can Change After Limited Battery Use



Not typical of all energy storage systems

- **Fuel economy standards are increasing.**
- **In the U.S., the fuel economy of a vehicle is determined by the EPA.**
- **The calorimeter can determine if the vehicle battery has a "break-in" period – in other words, the battery efficiency increases after cycling the battery.**
- **Knowing how your battery performs over time may prevent/reduce EPA fines for not meeting future fuel economy standards.**

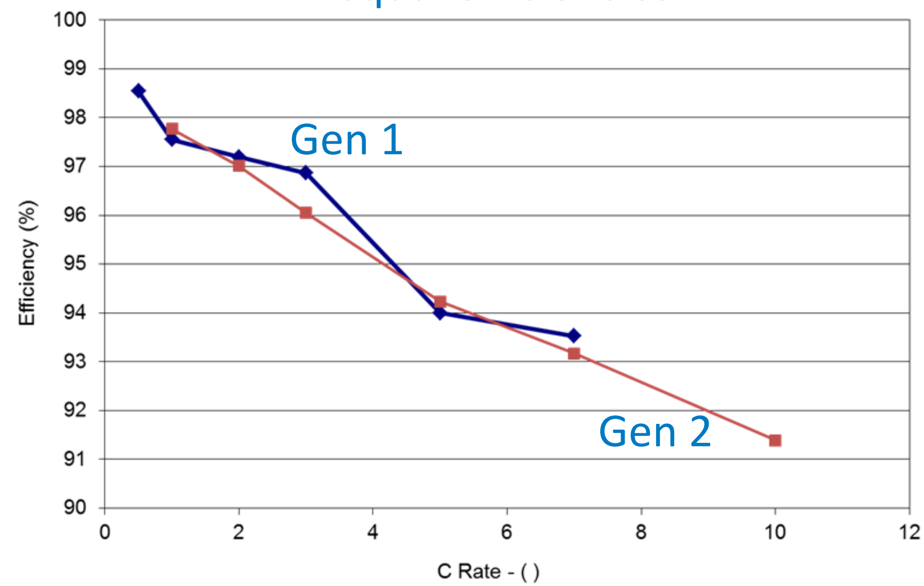
Efficiency Comparison of Successive Generations of Cells



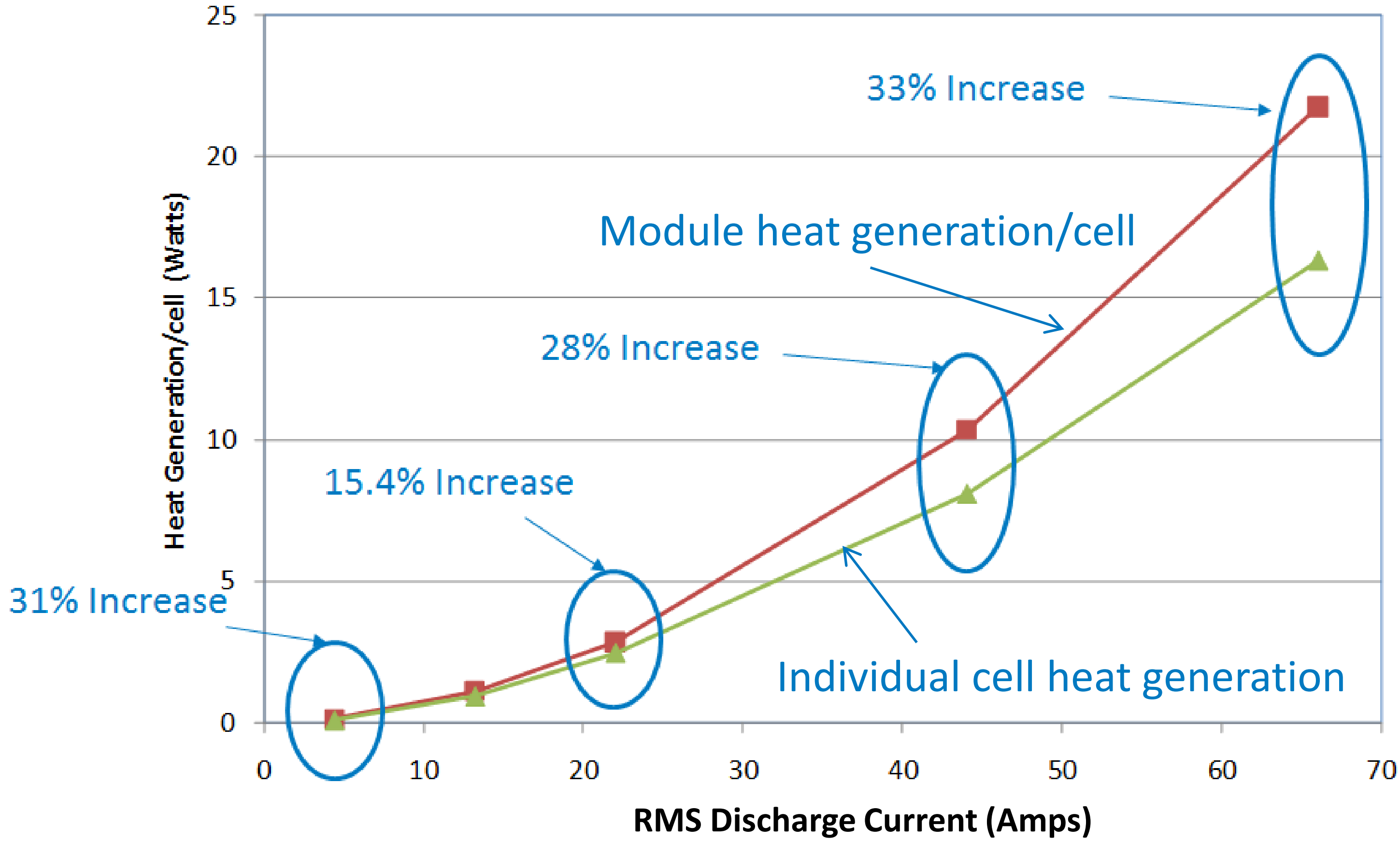
Full Discharge – 100% to 0% SOC: Testing over the entire discharge range of the cell gives the impression that the second-generation cell is less efficient.

Important to test the cells over the SOC range in which they will be used.

Partial Discharge – 70% to 30% SOC: Testing over the usage range of the cells shows that they have approximately equal efficiencies.



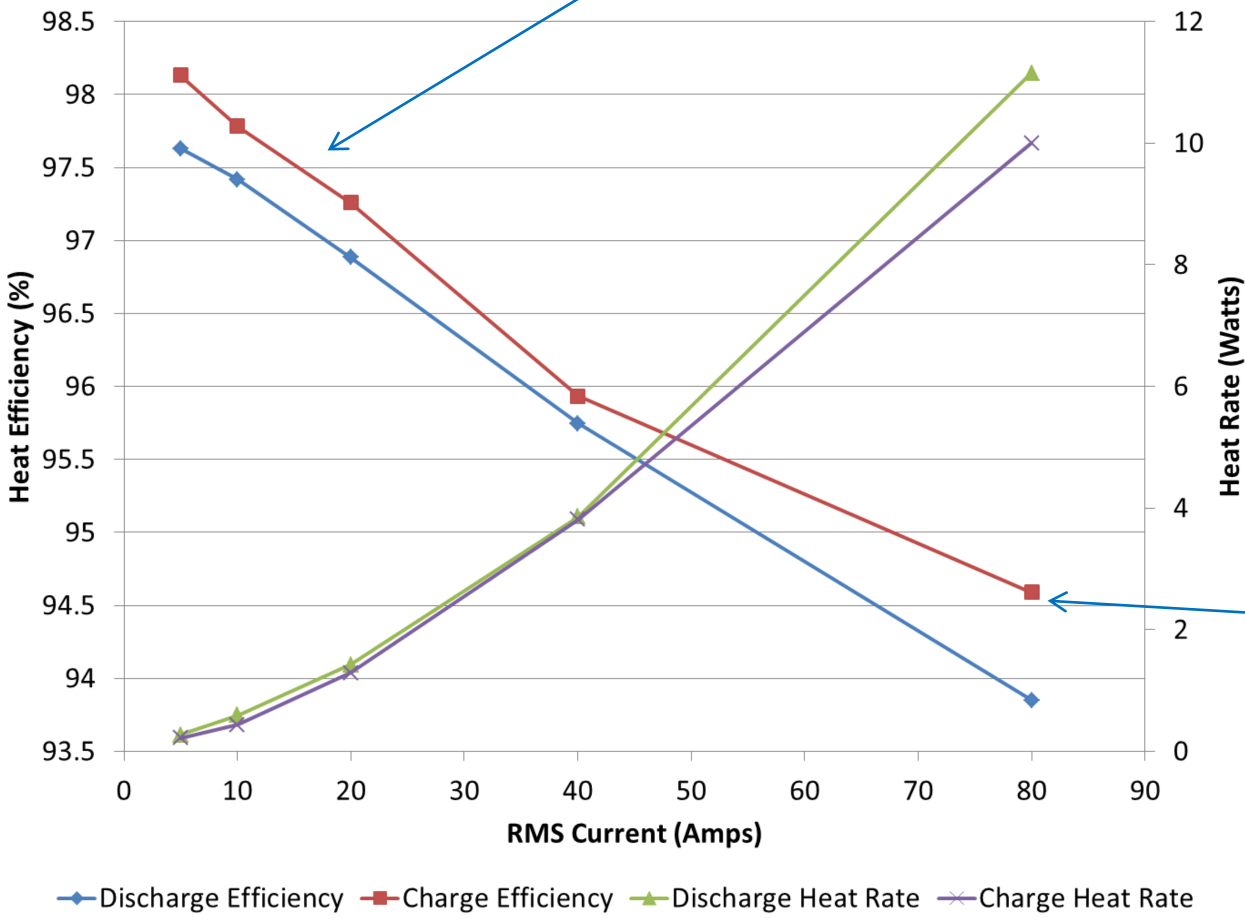
Cell versus Module Heat Generation



Heat generated by interconnects is important to understand in order to properly design a thermal management system

New Chemistries – Titanate Anodes

For the same current, the cell is more efficient under charge than discharge.



Charge impedance limiting Ah input at high rates