Battery Thermal Characterization

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Overview

Timeline

- **Project Start Date: 10/2004**
- **Project End Date: 9/2017**
- **Percent Complete: Ongoing**

(Supporting ongoing DOE/USABC battery developments)

Budget

- **Total Project Funding:**
  - DOE Share: 100%
  - Contractor Share: 0%
- **Funding Received in FY14: $535K**
- **Funding for FY15: $500K**

Barriers

- Decreased energy storage life at high temperatures (15-year target)
- Decreased battery performance at low temperatures
- High energy storage cost due to cell and system-integration costs
- Cost, size, complexity, and energy consumption of thermal management systems

Partners

- USABC – GM, Ford, Chrysler
- Envia
- Farasis
- JCI
- Leyden
- LGCPI
- Maxwell
- Saft
- SK Innovation

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
9/2014	Milestone	Report on thermal evaluation of advanced cells and battery packs	Complete
12/2014	Milestone	Present thermal data at USABC technical review meetings	Complete
3/2015	Milestone	Report on battery thermal data for USABC cells	Complete
6/2015	Milestone	Present thermal data at USABC technical review meetings	On Track
9/2015	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

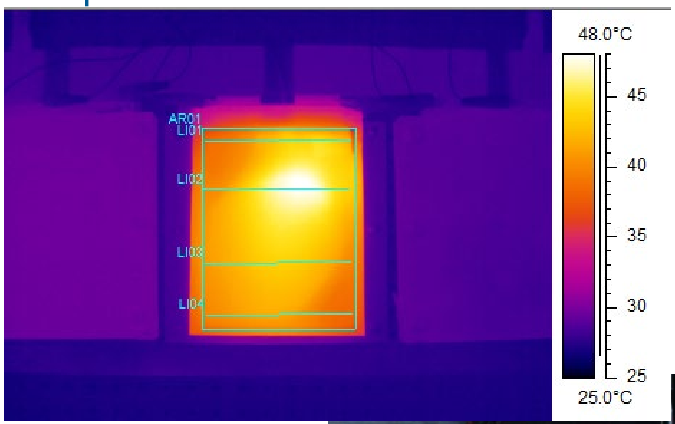
- **NREL provides critical thermal data to the battery manufacturers and OEMs that can be used to improve the design of the cell, module, pack and their respective thermal management systems.**
- **The provided data include infrared imaging results and heat generation of cells under typical profiles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

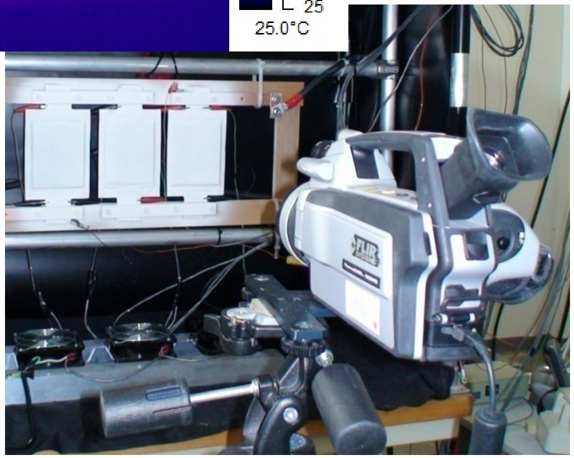
EV = electric vehicle; HEV = hybrid electric vehicle; OEM = original equipment manufacturer; PHEV = plug-in hybrid electric vehicle; UDDS = Urban Dynamometer Driving Schedule ; HWFET = Highway Fuel Economy Test

Thermal Testing – Approach

Thermal Imaging

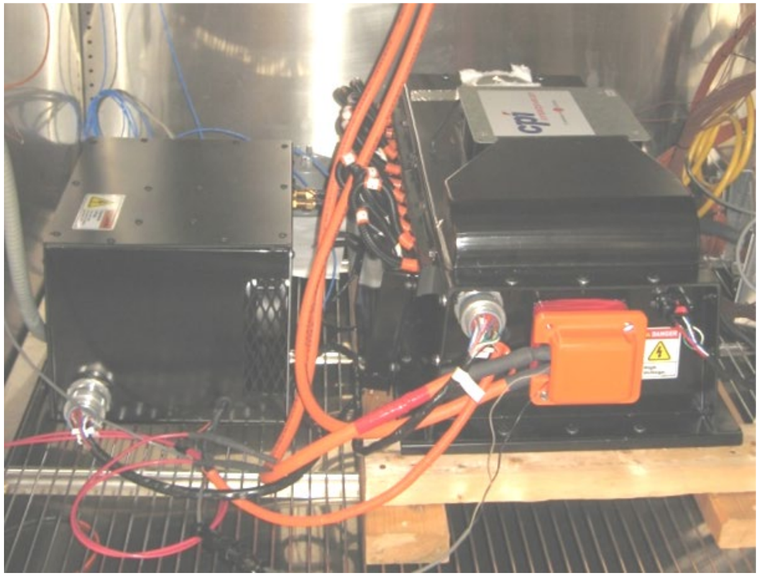
- **Temperature variation** across cell
- Profiles: US06 cycles, CC discharge/charge
- Unique testing method reducing environmental impacts





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

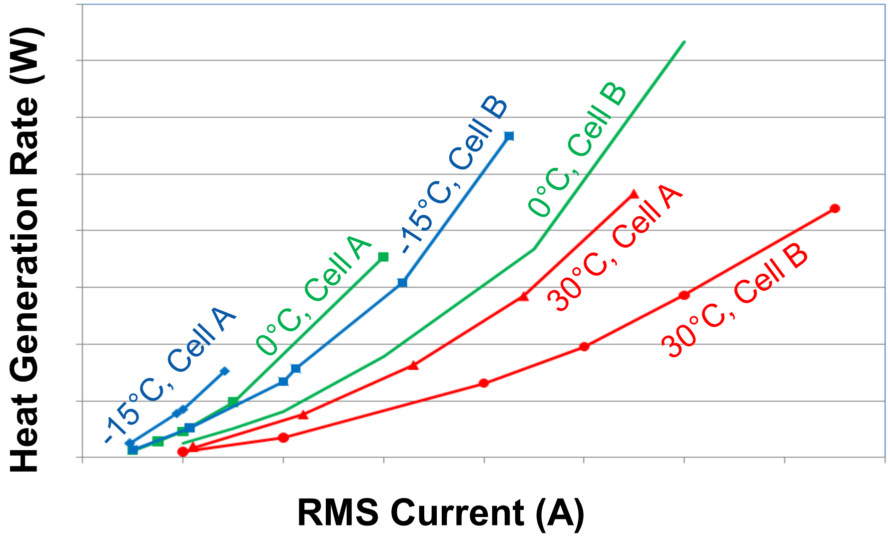
Photos by Kandler Smith, NREL

Heat Generation and Efficiency – Approach

Using state of the art isothermal battery calorimeters

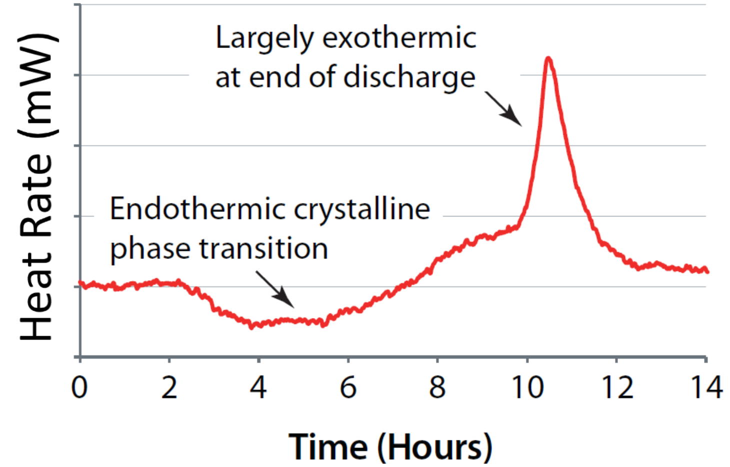
Top view of large calorimeter test chamber

Photo by Dennis Schroeder, NREL



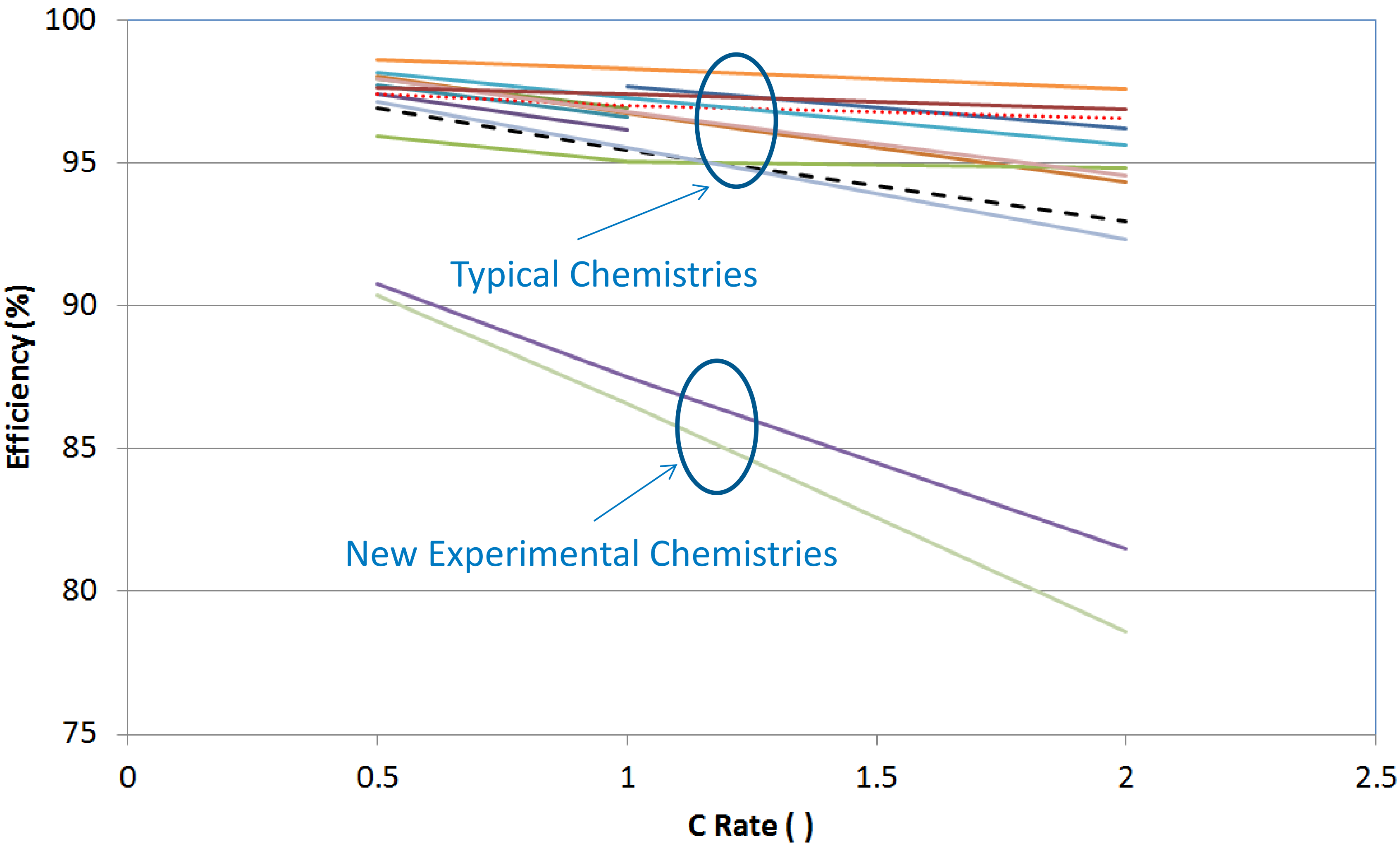
- **Heat generation**, heat capacity, and efficiency
- Test Temperature Range: -30°C to +45°C
- Profiles: USABC and US06 cycles, const. current

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 (°C)	-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 FY14 and FY15 at 30°C Under Full Discharge from 100% to 0% SOC

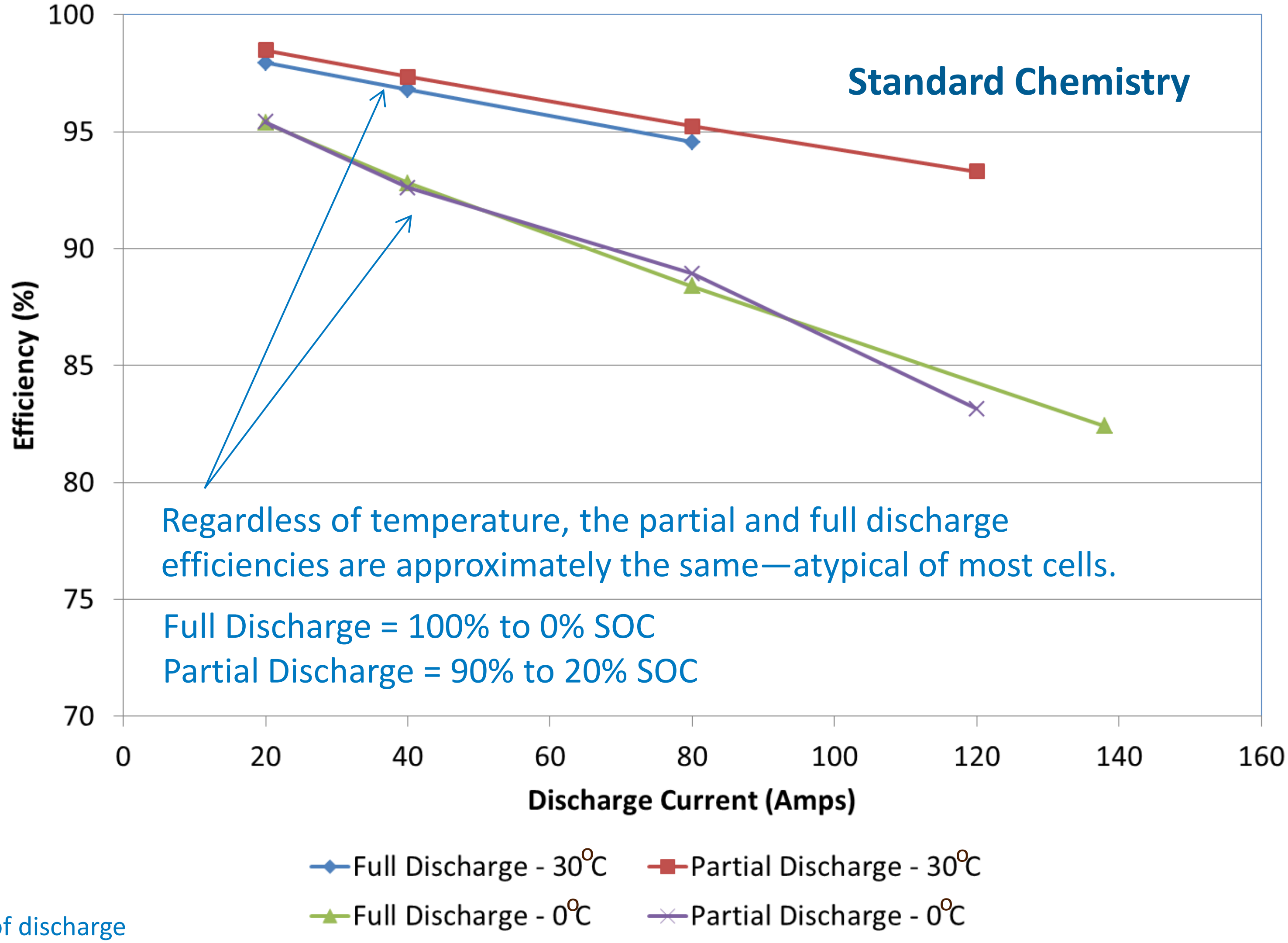
Technical Lessons Learned



SOC = state of charge

EV Cells Improving Efficiency Over Entire DOD Range

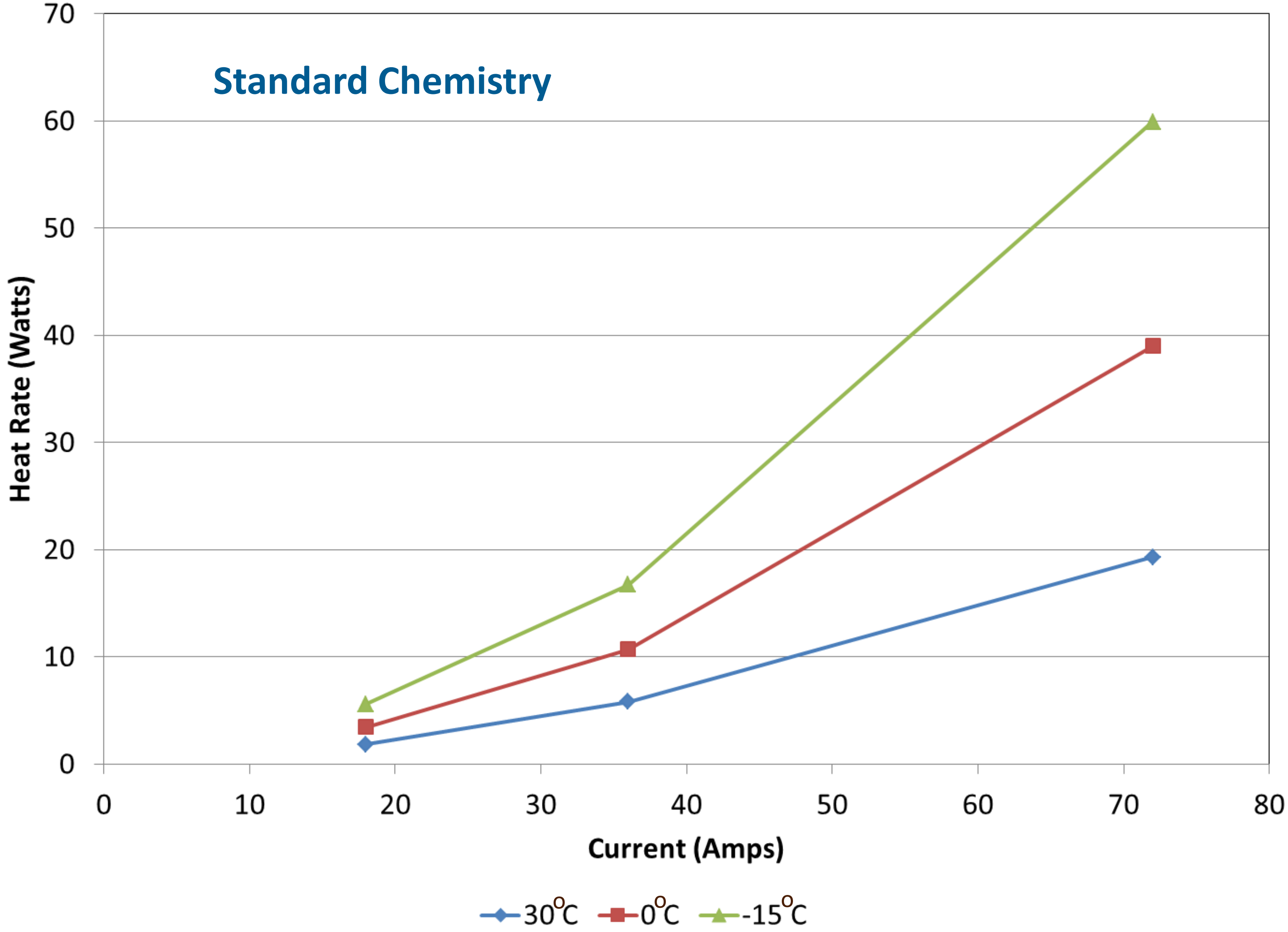
Technical Lessons Learned



DOD = depth of discharge

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

Technical Lessons Learned



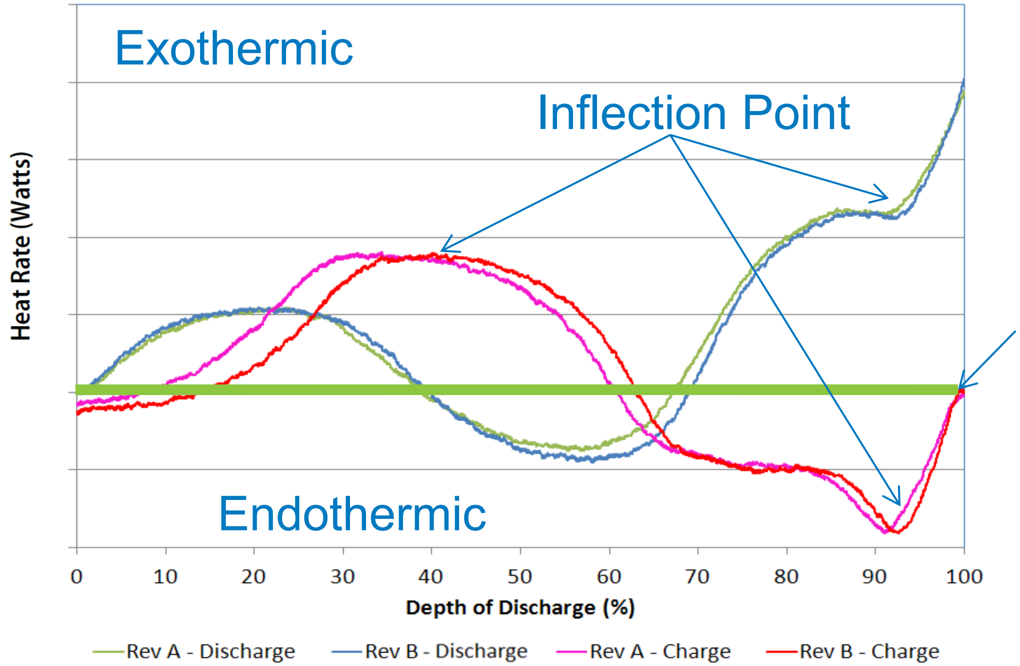
Low-Current Entropic Heating

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.

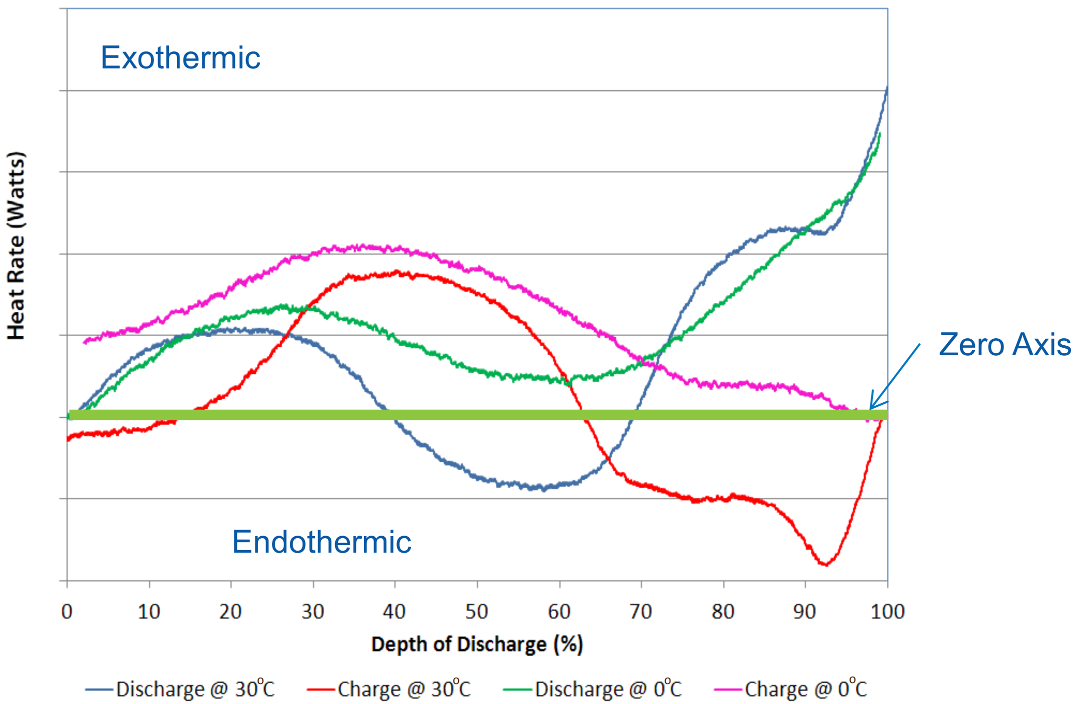
Cycling the battery at the inflection points may cause cracks in the anode or cathode, which may lead to decreased performance and life.



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

Entropic Studies Over a Temperature Range

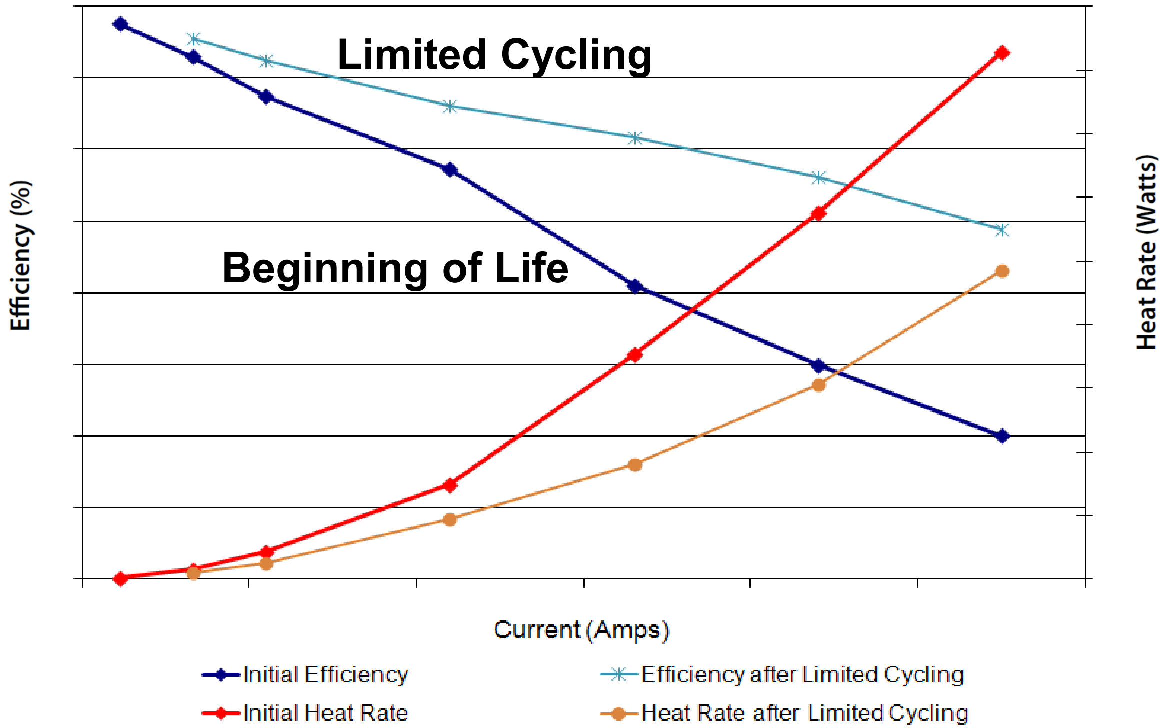
Technical Lessons Learned



- **In general, batteries are less efficient at lower temperatures due to a resistance increase of the battery components and a resistance to ionic diffusion.**
- **Entropic studies can determine if low-temperature additives are positively affecting the performance of the battery.**

Efficiency Changes with Limited Cycling

Technical Lessons Learned



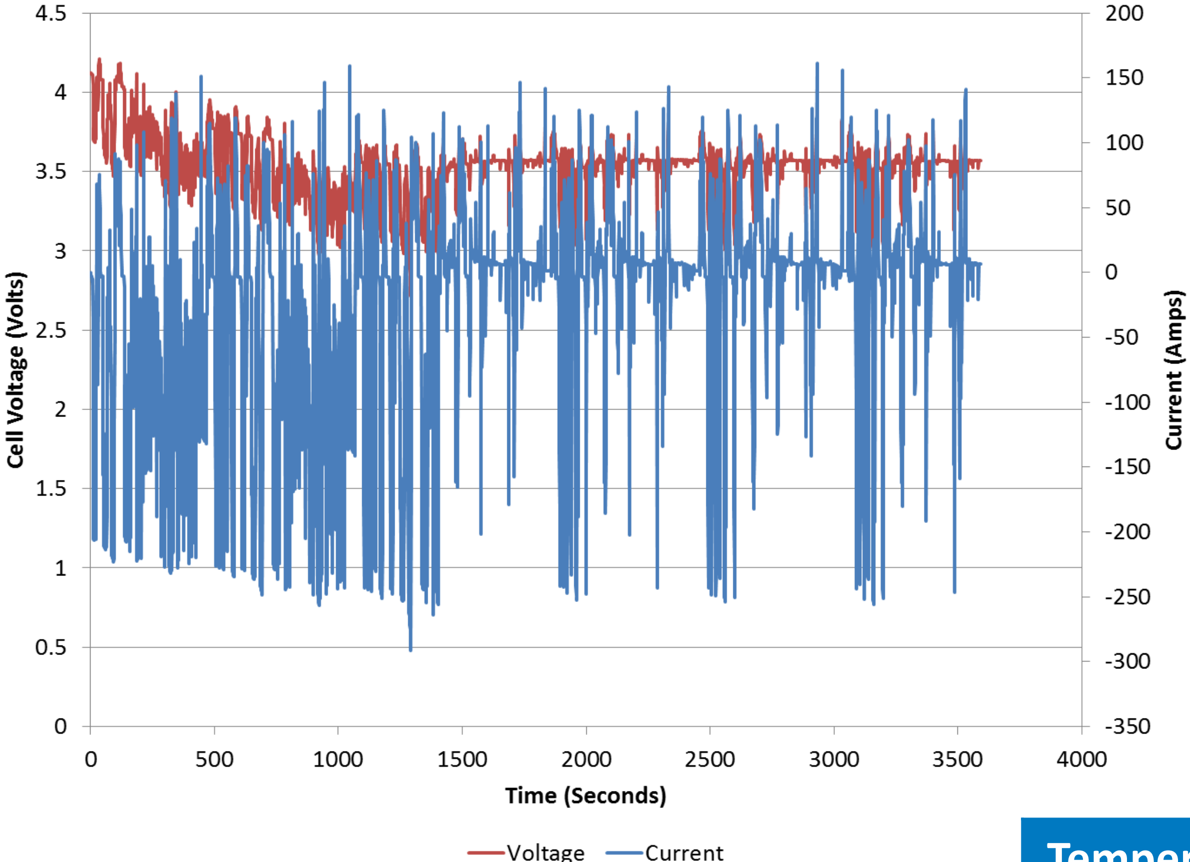
Not typical of all energy storage systems.

- **Fuel economy standards are increasing.**
- **In the United States, the fuel economy of a vehicle is determined by the Environmental Protection Agency (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.**

Heat Generation from PHEV40 US06 CD/CS Cycle

Technical Lessons Learned

CD = charge depleting
CS = charge sustaining



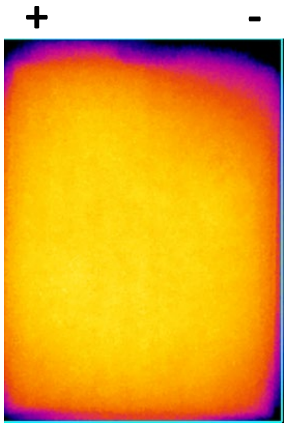
Temperature can have a large effect on efficiency and heat rate.

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

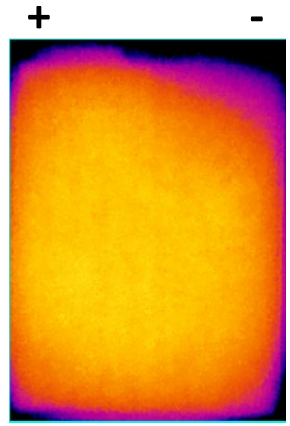
Temperature (°C)	Efficiency (%)	Heat Rate (watts/cell)
30	90.6	16.1
0	81.5	30.0

IR Images of PHEV Cell at End of 2C Constant Current Discharge

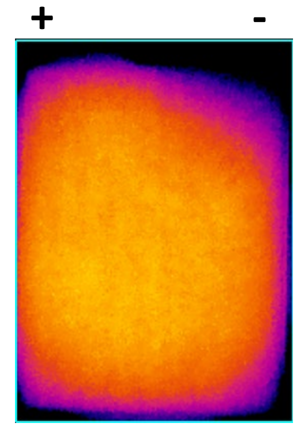
Technical Lessons Learned



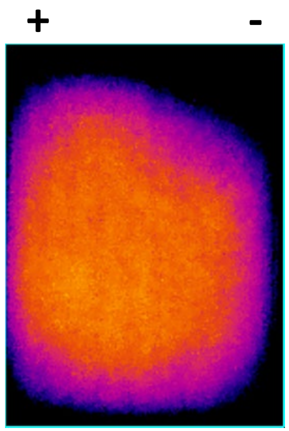
5°C Temp Spread



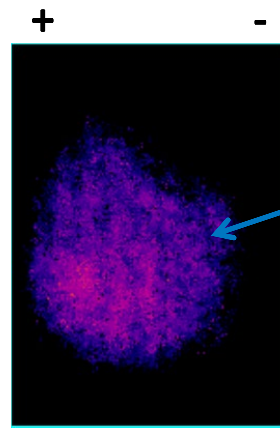
4°C Temp Spread



3°C Temp Spread



2°C Temp Spread



1°C Temp Spread

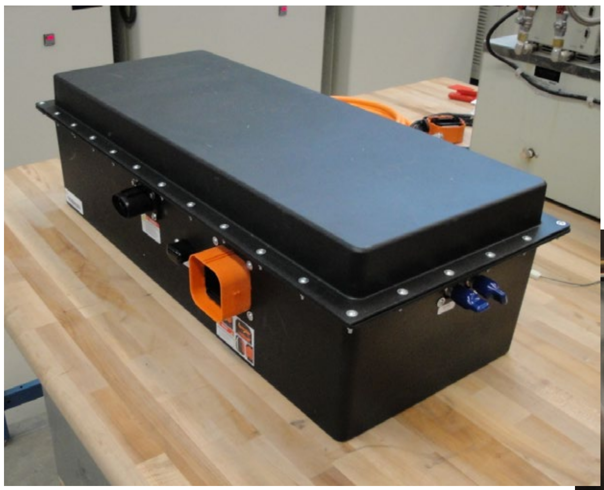
Heat being generated at the center of the cell—biased toward the positive terminal.

Infrared (IR) imaging pinpoints where the heat is being generated in the cell.

Pack Thermal Temperature Studies

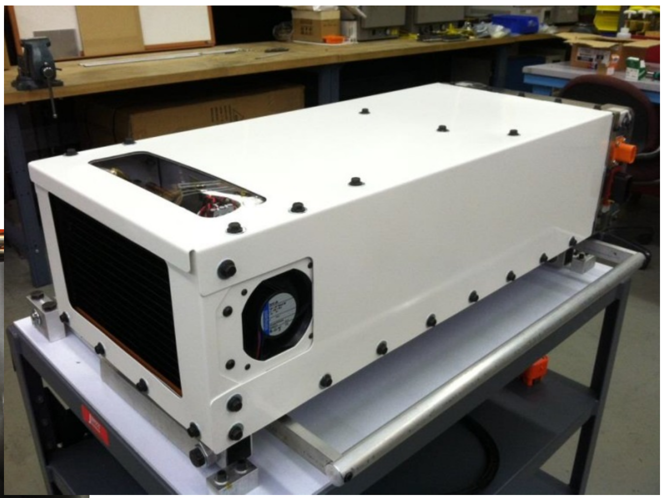
Technical Lessons Learned

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

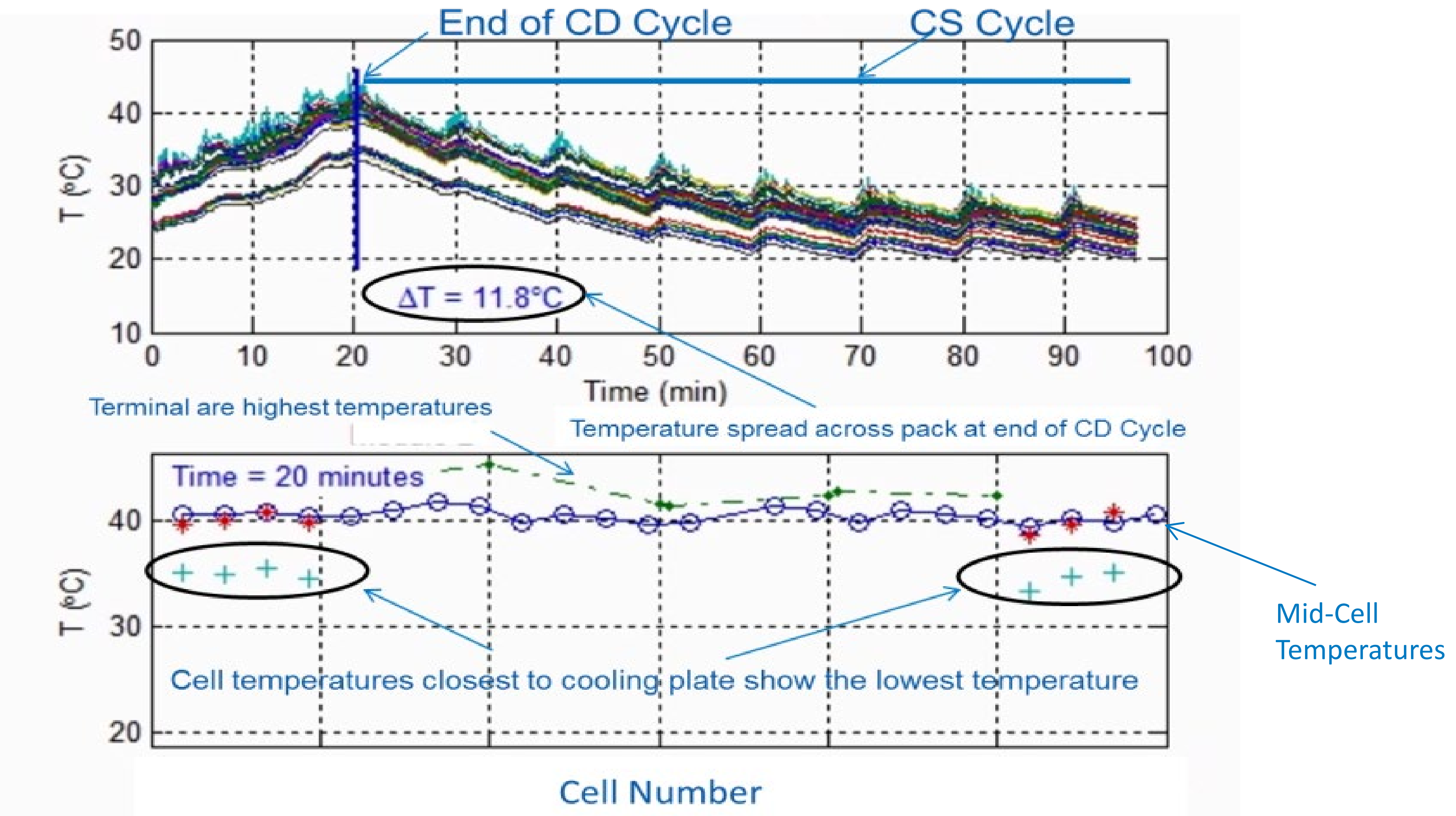


LGCPI

Photos by Dirk Long, NREL

Thermal Management System Performance Under a PHEV Drive Cycle

Technical Lessons Learned



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

"The reviewer indicated that the PI has taken the correct approach when looking at or observing useable ranges of the devices under evaluation. The reviewer hoped that did not curtail a greater objective to broaden the useable range for increased performance goals."

In conjunction with USABC, we are assessing new chemistries along with new technologies that expand the useable temperature range of energy storage systems. We are also expanding our test protocols to incorporate more drive cycles along with specific constant current charge/discharge profiles. The data will aid in the development of an efficiency/heat generation model that can be used by the manufacturer to predict how much will be produced under varying loads and environmental conditions.

Collaborators

- **USABC partners Chrysler, GM, and Ford**
- **USABC Contractors**
  - Farasis
  - JCI
  - Leyden
  - LGCPI
  - Maxwell
  - SK Innovation
  - Saft

Remaining Challenges and Barriers

- **Address life issues at high and low temperatures—15-year target.**
- **Address high energy storage cost due to battery packaging and integration costs.**
- **Reduce the cost, size, complexity, and energy consumption of thermal management 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, Chrysler, 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 such as room temperature refrigerants.

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 has been shared with the battery developers.
- **Thermal properties are used for the thermal analysis and design of improved battery thermal management systems to support achieve life and performance targets.**