NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Battery Thermal Characterization

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Project ID # ES204

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Overview

Timeline

- Project start date: 10/2017
- Project end date: 10/2021
- Percent complete: Ongoing

Budget

- Total project funding
  - DOE share: 100%
  - Contractor share: 0%
- Funding received in FY 2016: $500k
- Funding for FY 2017: $600k

Barriers

- Decreased battery life at high temperatures
- 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

- United States Advanced Battery Consortium (USABC) – Fiat-Chrysler, Ford, GM
- LGCPI
- Maxwell
- Saft
- Seeo
- Envia
- Farasis
- Argonne National Laboratory (ANL)
- Idaho National Laboratory (INL)
- Sandia National Laboratory (SNL)

Relevance of Battery Thermal Testing and Modeling

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

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
- Identify how charges to the battery chemistry and cell design affect the cells' efficiency and performance
- To quantify the impacts of temperature and duty cycle on energy storage system life and cost
- Work with the cell manufacturers to identify new thermal management strategies that are cost effective.

USABC = U.S. Advanced Battery Consortium

U.S. DRIVE - United States Driving Research and Innovation for Vehicle Efficiency and Energy

Milestones

Month / Year		Description of Milestone or Go/No-Go Decision	Status
9/2016	Milestone	Report on thermal evaluation of advanced cells and battery packs	Complete
12/2016	Milestone	Present thermal data at USABC technical review meetings	Complete
3/2017	Milestone	Report on battery thermal data for USABC cells during first half of FY17	Complete
6/2017	Milestone	Present thermal data at USABC technical review meetings	On Track
9/2017	Milestone	Report on battery thermal data collected on USABC battery cells/packs for FY17	On Track

Approach – Thermal Testing

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
  - U.S. DRIVE profiles

Measurements

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

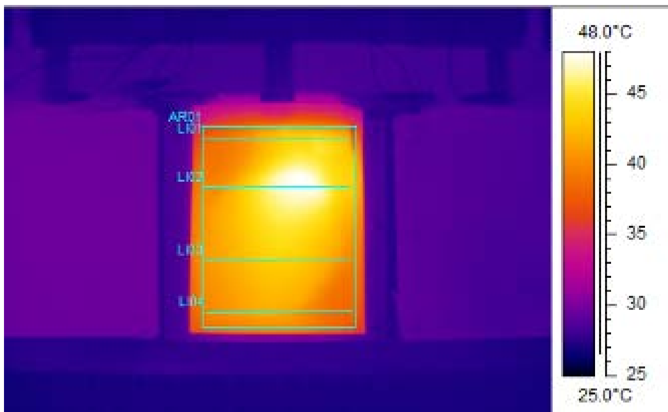
- NREL provides critical thermal data to the battery manufacturers and OEMs that can be used to improve the design of the cell, module, and pack and their respective thermal management systems.
- The provided data include infrared imaging results and heat generation of cells under typical profiles for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

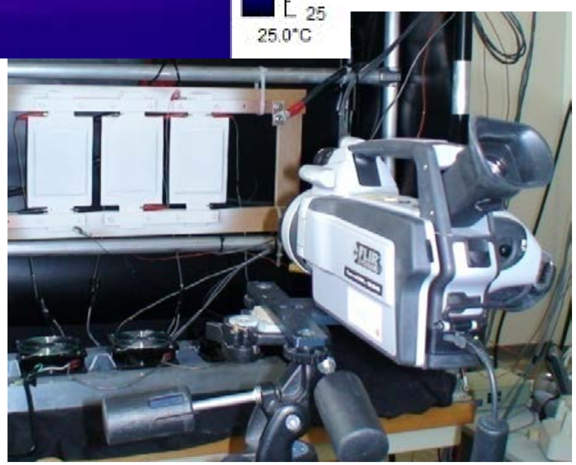
EV = electric vehicle; HEV = hybrid electric vehicle; OEM = original equipment manufacturer; PHEV = plug-in hybrid electric vehicle; HWFET = Highway Fuel Economy Test; UDDS = Urban Dynamometer Driving Schedule

Approach – Thermal Testing

Thermal Imaging

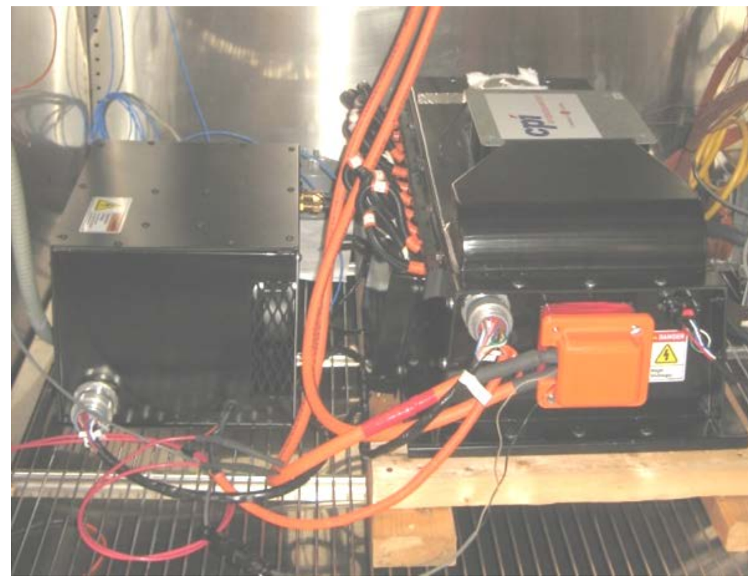
- **Temperature variation** across cell
- Profiles: US06 cycles, CC discharge/charge
- Unique non-destructive testing method to identify thermal areas of concern





Thermal Management Performance

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



Photos by Kandler Smith, NREL

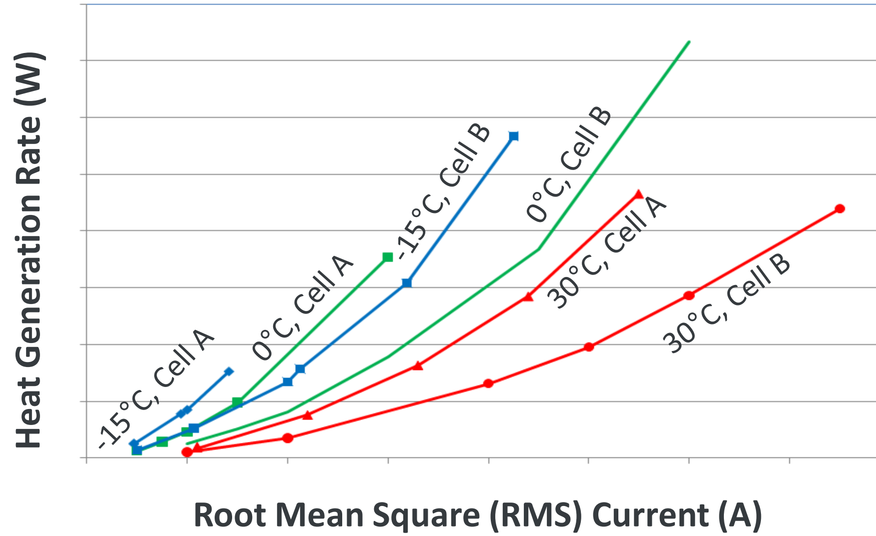
Results reported to DOE, USABC, and battery developers

Approach – Heat Generation and Efficiency

Using state-of-the-art isothermal battery calorimeters

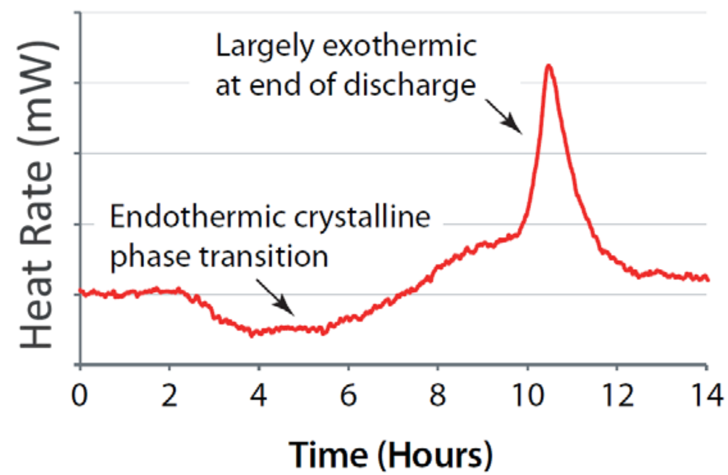
Top view of large calorimeter test chamber

Photo by Dennis Schroeder, NREL



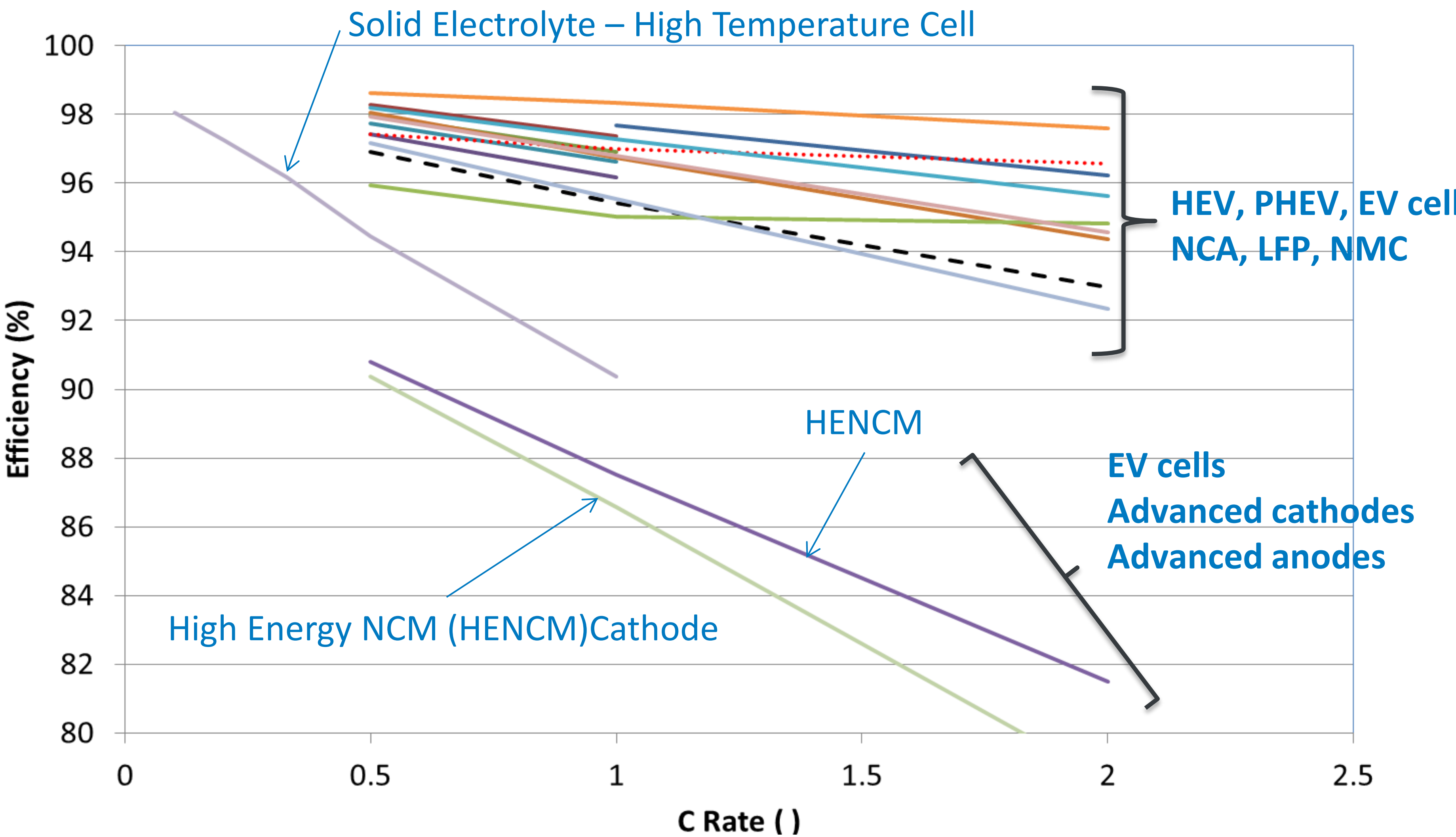
- **Heat generation**, heat capacity**,** and efficiency
- Test temperature range: -30°C to +45°C
- Profiles: USABC and US06 cycles, CC

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 (°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



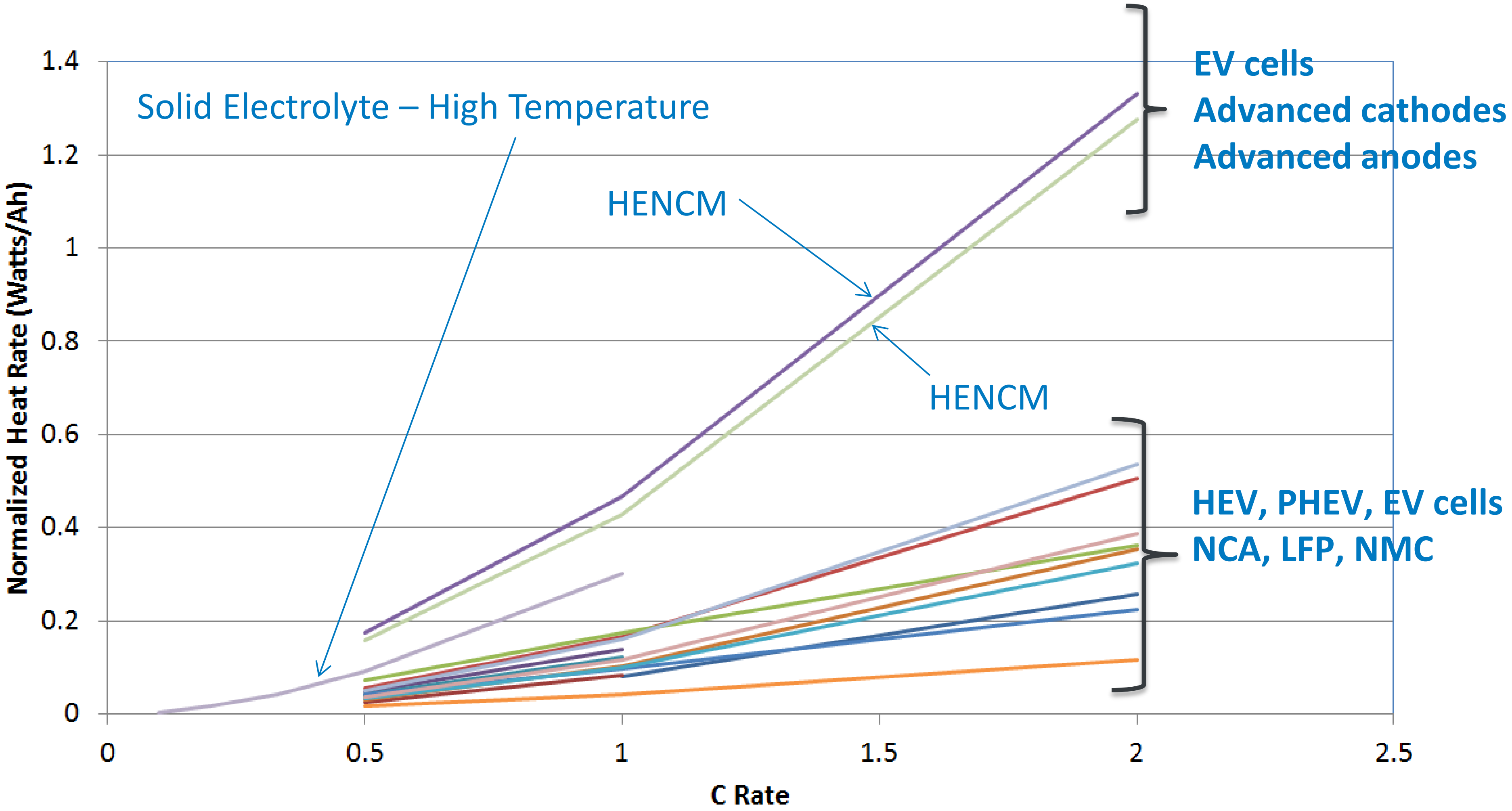
Efficiency Comparison of State-of-the-Art (SOTA) Cells

Technical Accomplishments

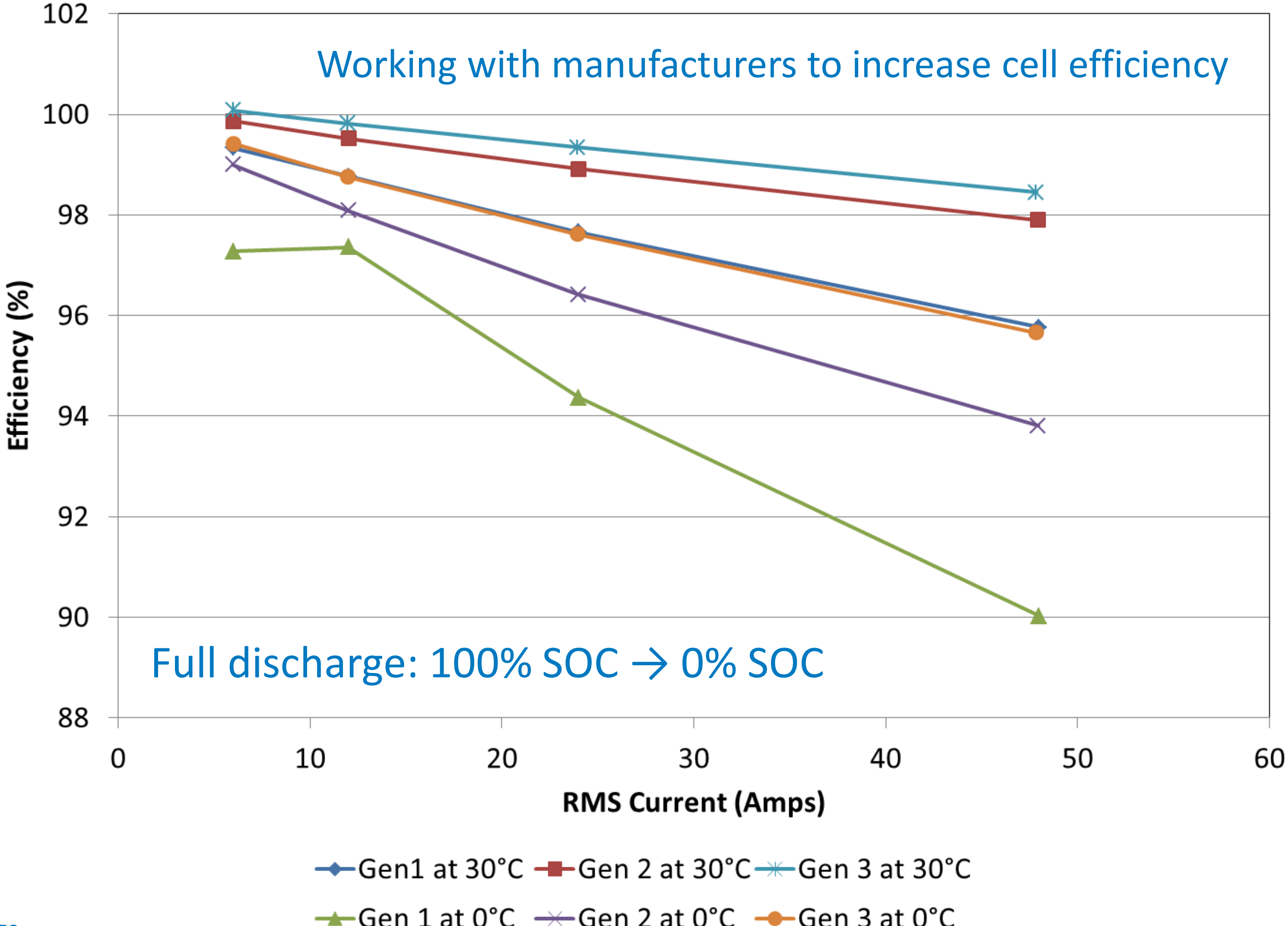


Heat Rate Comparison of SOTA Cells

Technical Accomplishments

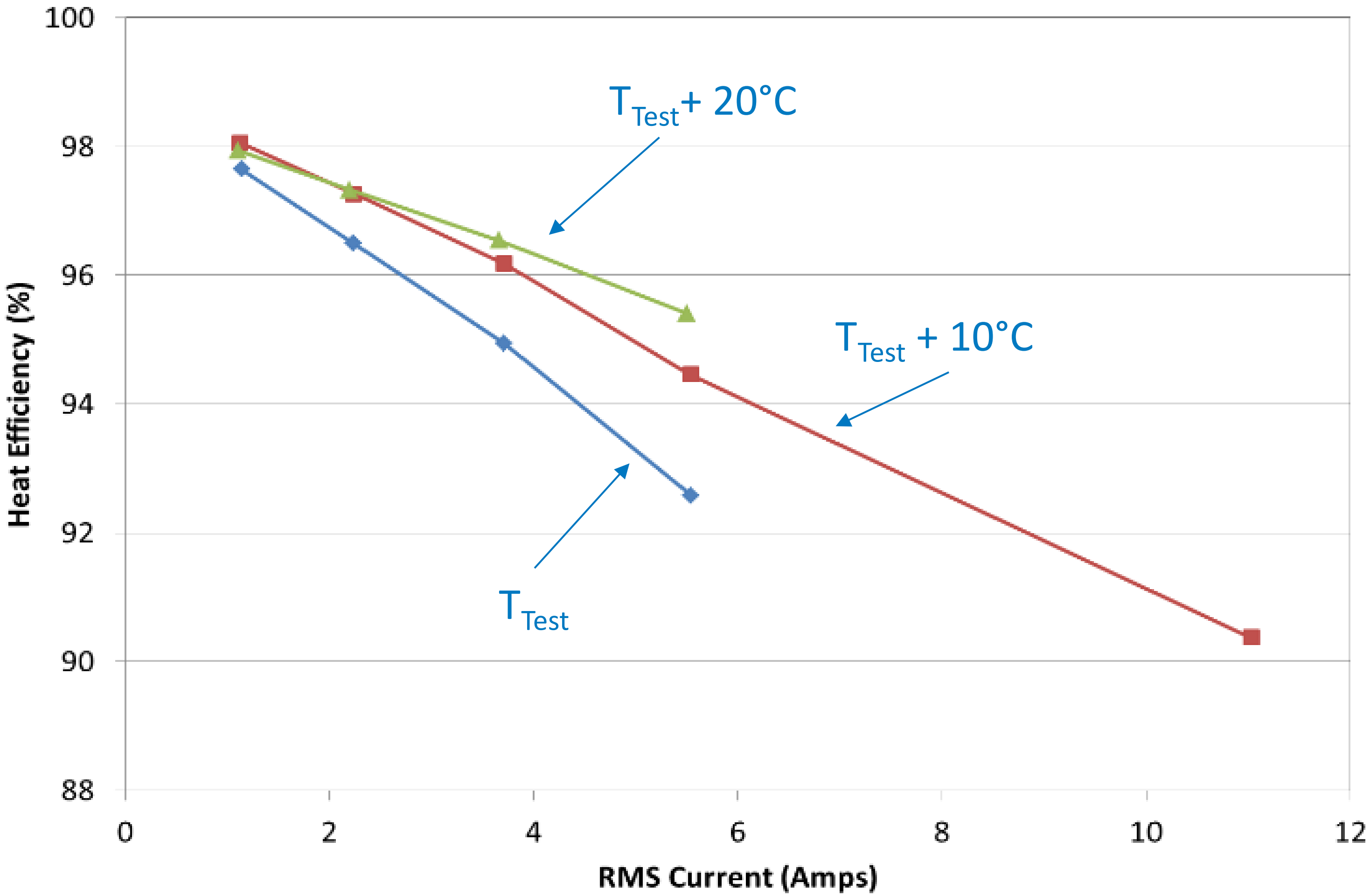


Technical Accomplishments



SOC = State of Charge

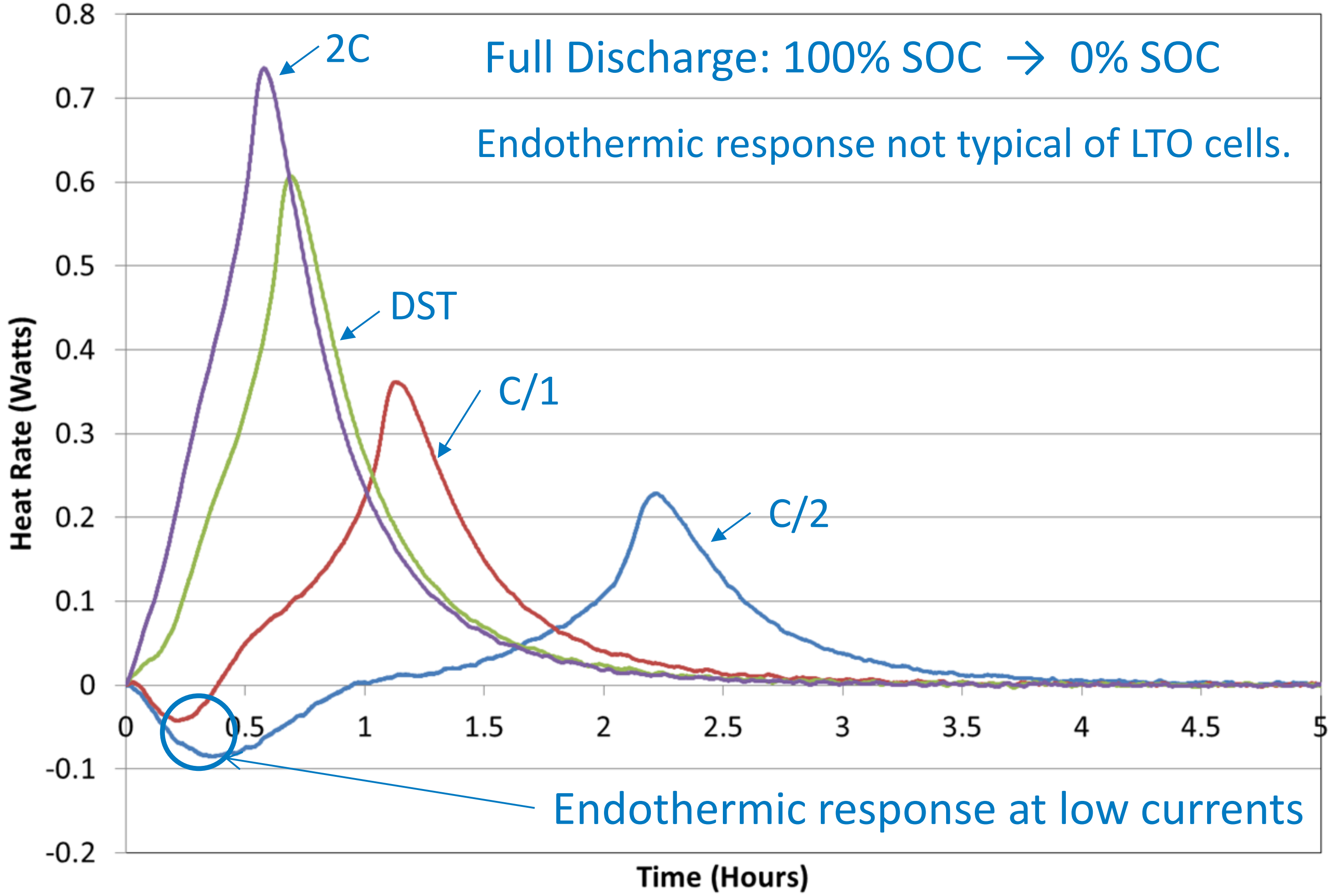
Technical Accomplishments



Solid electrolyte cells have lower efficiencies even when used at higher temperatures.

Calorimetry Testing Can Identify Entropic Heating/Cooling

Technical Accomplishments



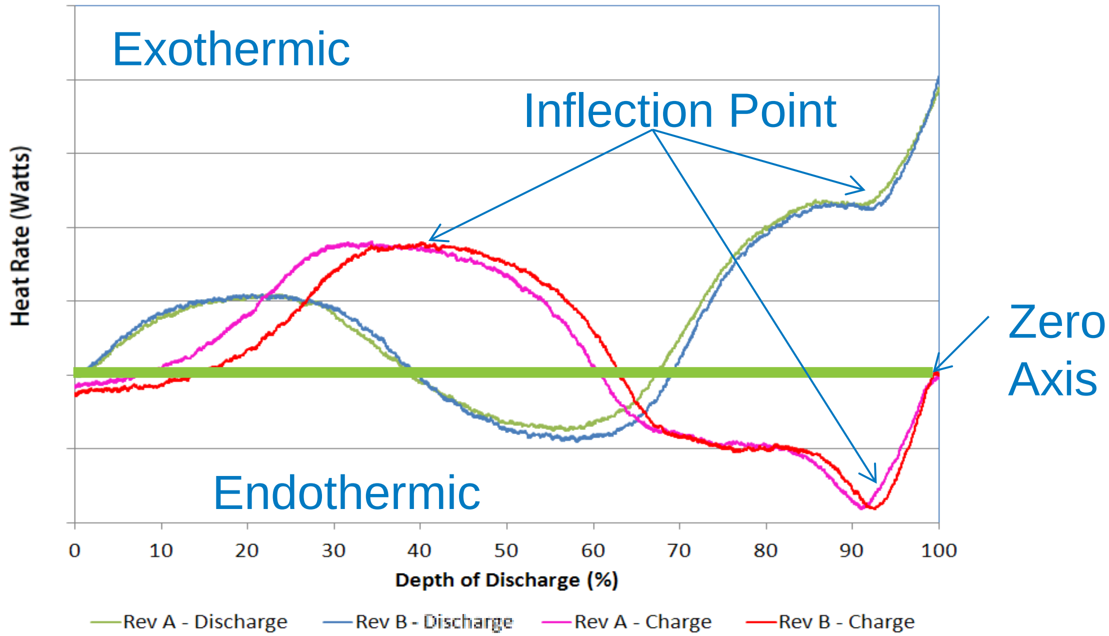
LTO – Lithium Titanate

Technical Accomplishments

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.

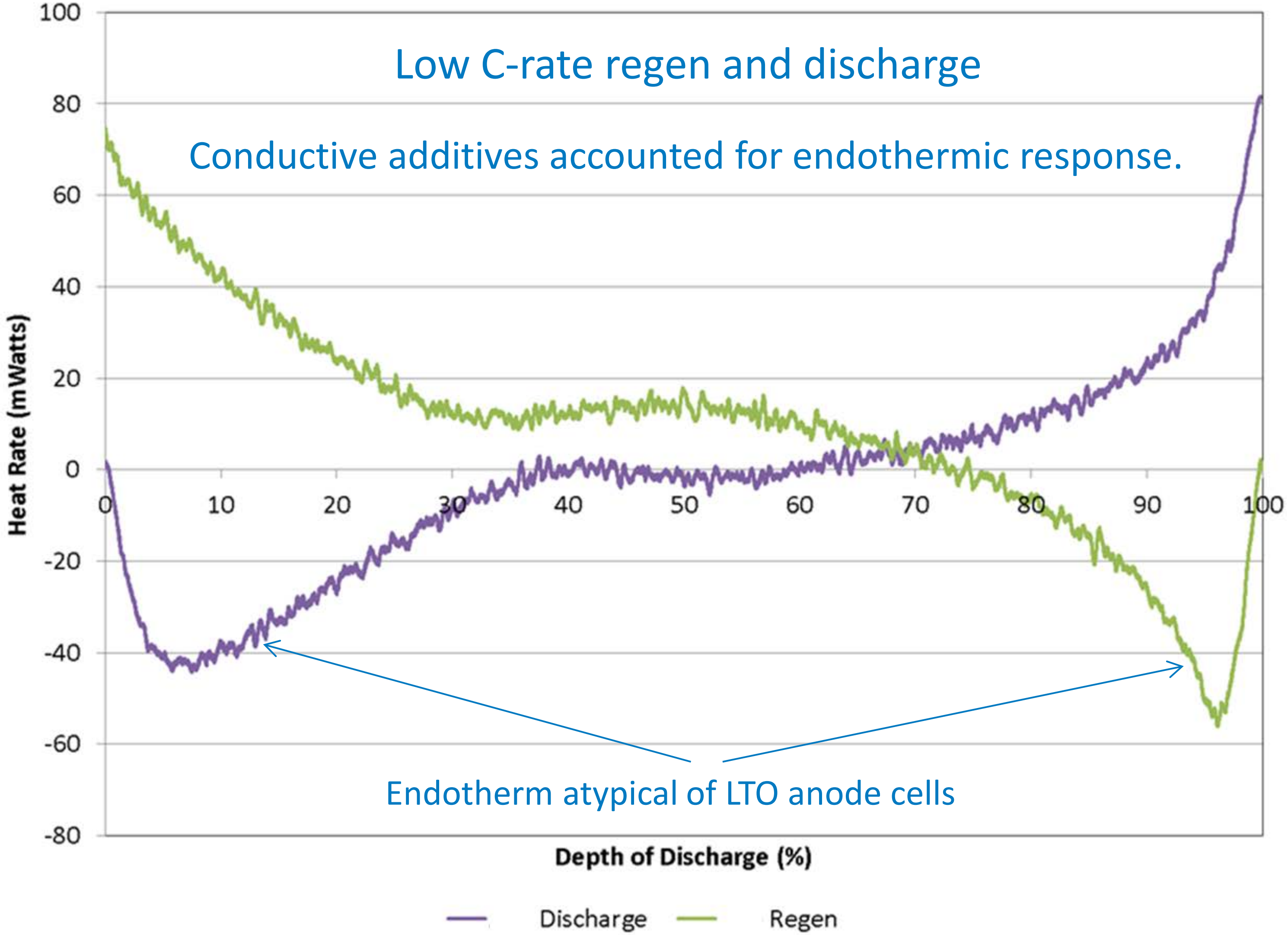
Cycling the battery at the inflection points may cause cracks in the anode or cathode, which may lead to decreased performance and life.



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

Additives Can Affect the Electrochemistry of the Cell

Technical Accomplishments



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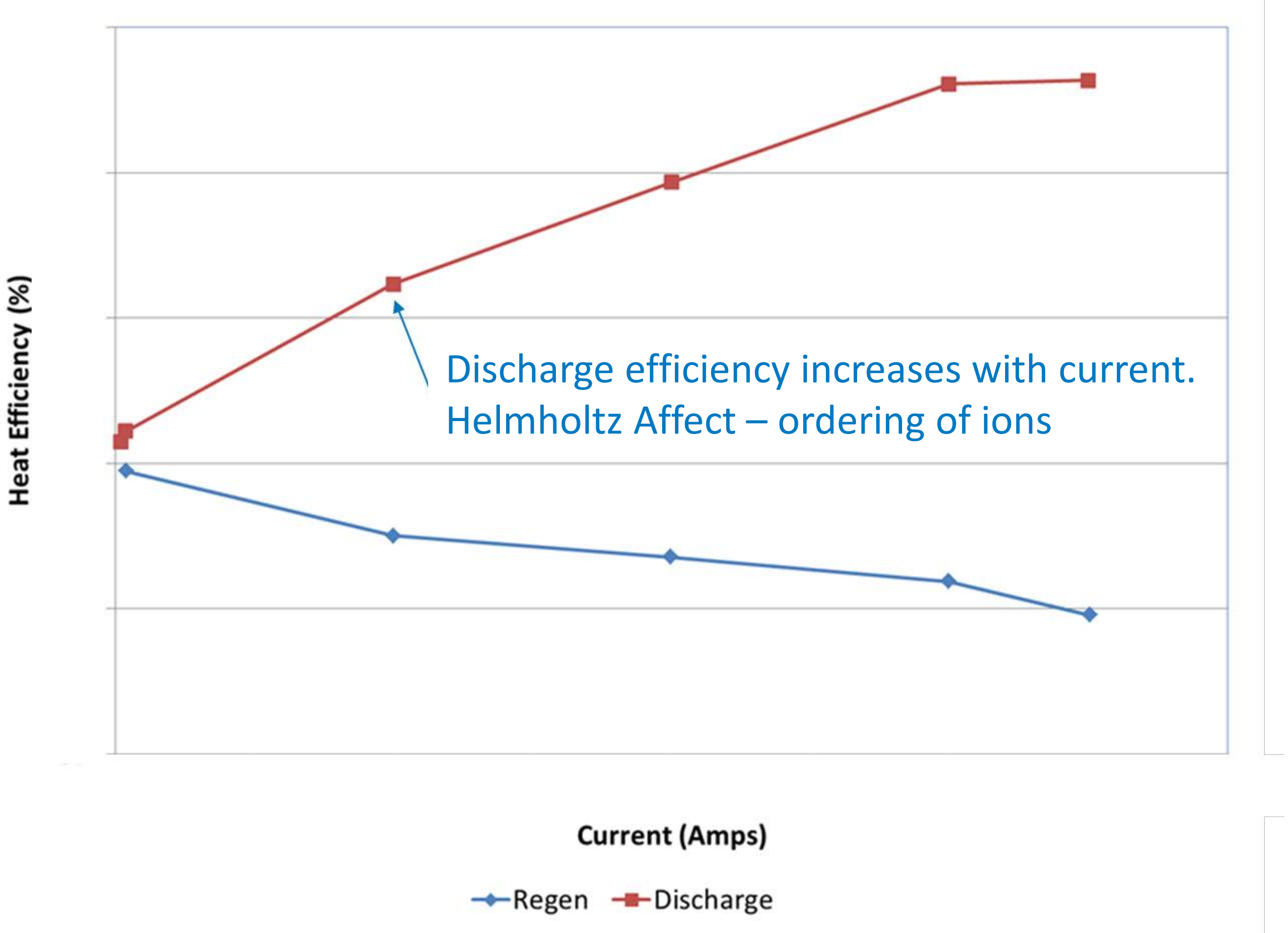
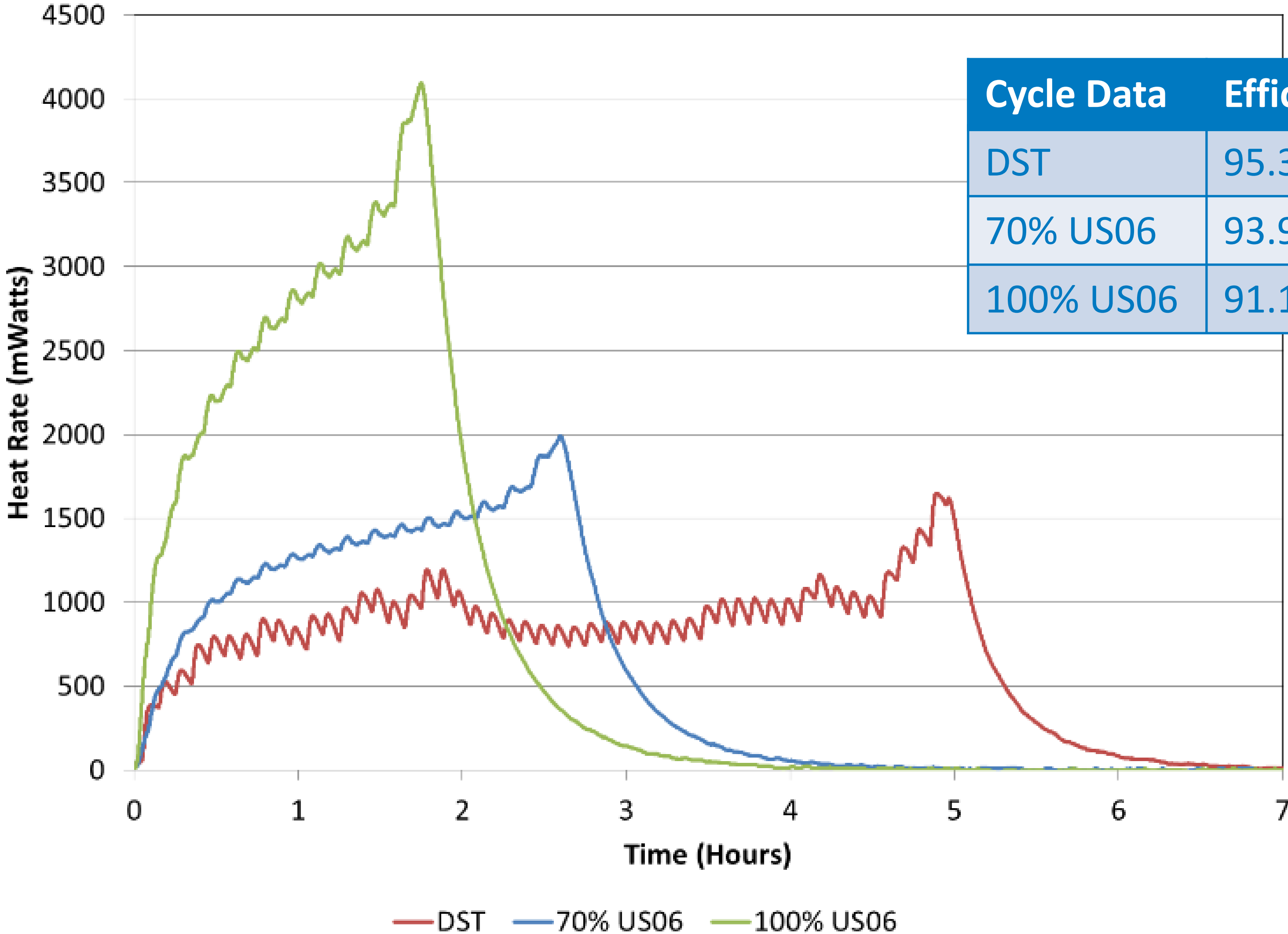


Heat Generation under Various Drive Cycles

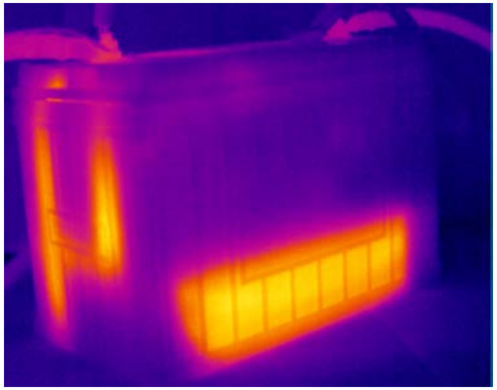
Technical Accomplishments

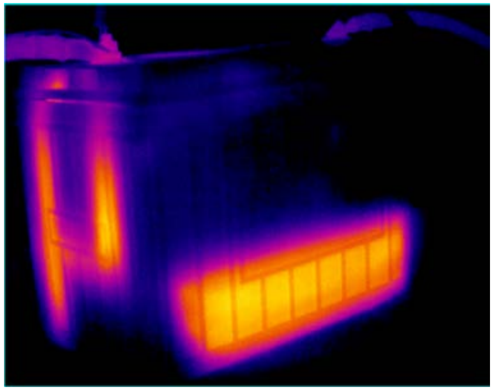
I_{soc} = 100%; $Final_{soc}$ = 0%

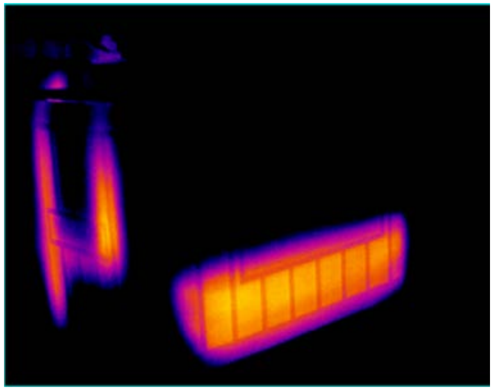


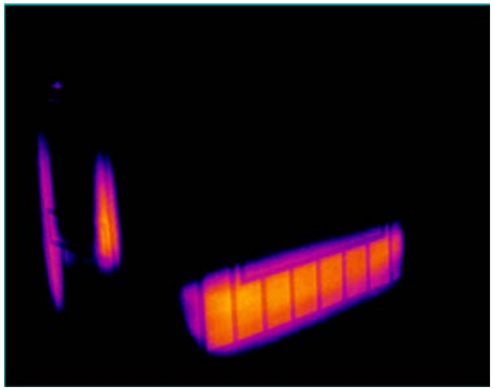
Cycle Data	Efficiency
DST	95.3
70% US06	93.9
100% US06	91.1

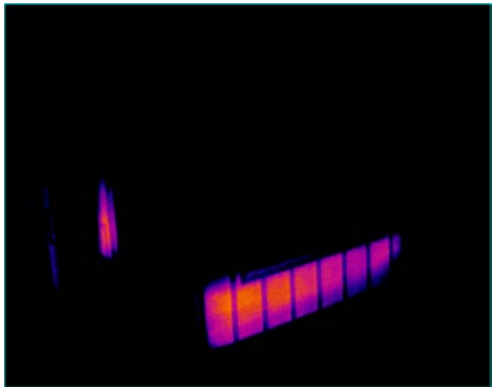
Technical Accomplishments


Δ Temp Spread


Δ Temp Spread - n°C


Δ Temp Spread – 2n°C


Δ Temp Spread – 3n°C


Δ Temp Spread – 4n°C

Heat being generated at bottom and center of Module

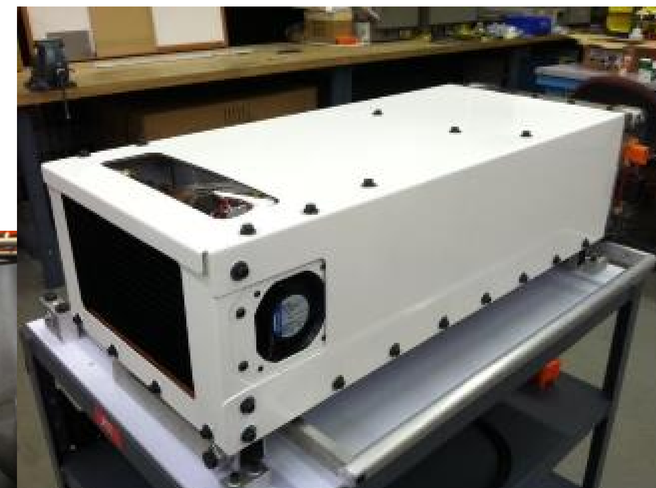
Infrared (IR) imaging pinpoints where the heat is being generated in the cell.

Technical Accomplishments

NREL 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

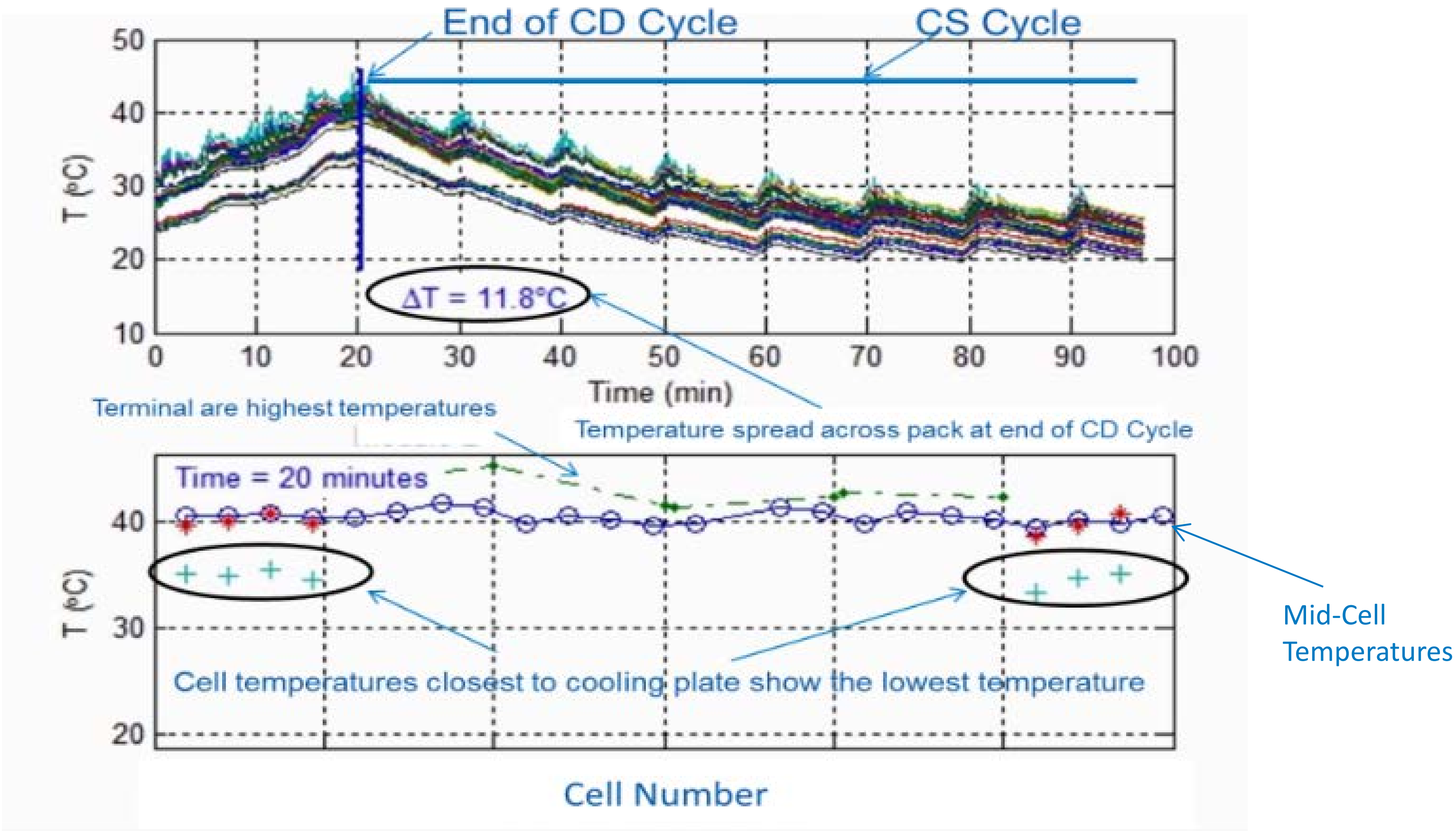
JCS



LGCPI

Photos by Dirk Long, NREL

Technical Accomplishments



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.

CD = charge depleting
CS = charge sustaining

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

Technical Accomplishments

Program Targets		Units	USABC Goals*					Program Target
			EV	PHEV			48V	
Key Parameters	Parameter Details			PHEV-20	PHEV-40	xEV-50		
Operational Life @30°C		[years]	15					
Operating Environment		[°C]	-30 to +52					
Pack Temperature Uniformity	ΔT: Cell-to-Cell	[°C]	< 3					
Cell Temperature Uniformity	ΔT: Cell Surface	[°C]	< 3					
System Efficiency	Ambient (unconditioned)	[ratio] Q/P**	> 15					
	Active		> 4					
Weight	In Pack Components Only	[kg]	< 5.3	< 5.6	< 9.6	< 12	< 1	
	Pack + Vehicle Connections		< 11.5	< 8.4	< 14.4	< 18	< 1.2	
Volume	In Pack Components Only	[L]	< 13.5	< 11.75	< 20	< 25	< 2	
	Pack + Vehicle Connections		< 22.5	< 16.5	< 28	< 35	< 2.8	
System Cost		$	< 112 @100k units	< 44 @100k units	< 68 @100k units	< 85 @100k units	< 6 @250k units	

Evaluating new thermal management systems according to USABC guidelines.

CD = charge depleting
CS = charge sustaining

Response to Previous Year Reviewers' Comments

- Reviewer Comment: The reviewer said that it would be nice to see more collaboration between the experimental data produced by NREL and the battery models produced by the other national laboratories.

- Presenter Reply: The data is being shared with Argonne National Laboratory for their Bat-Pac models. Recently, ANL and NREL have also been sharing information on battery heating for extreme fast charging studies.

Response to Previous Year Reviewers' Comments

- Reviewer Comment: The reviewer remarked that the plots of heat rate during discharge of various cell chemistries was interesting, but rather than using a constant C discharge rates, it would be nice to see the dynamic stress test (DST) cycle used with multipliers, for example, or possibly a comparison of charge versus discharge heating rates. The reviewer pointed out that it is not easy to size a thermal system based on constant current (CC) discharges alone.

- Presenter Reply: The data in the presentation is a subset of all the data collected at NREL. We perform both CC discharge and charge pulses on the batteries to better inform the thermal models. We also perform different drive cycles on the batteries for the intended battery application, for example, a US06 CD and CS cycle for a PHEV cell. The discharge data alone would limit the accuracy of the model, but by generating data for charge/discharge and drive and DST cycles, we have a more complete picture of the heat generation within the cell.

Collaborator

- USABC Partners – Fiat-Chrysler, Ford, and GM
- USABC Contractors – Technologies evaluated at NREL
    - Envia
    - Farasis
    - LGCPI
    - Maxwell
    - Saft
    - Seoo
- National Labs
    - Argonne National Laboratory (ANL)
    - Idaho National Laboratory (INL)
    - Sandia National Laboratory (SNL)

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 Research

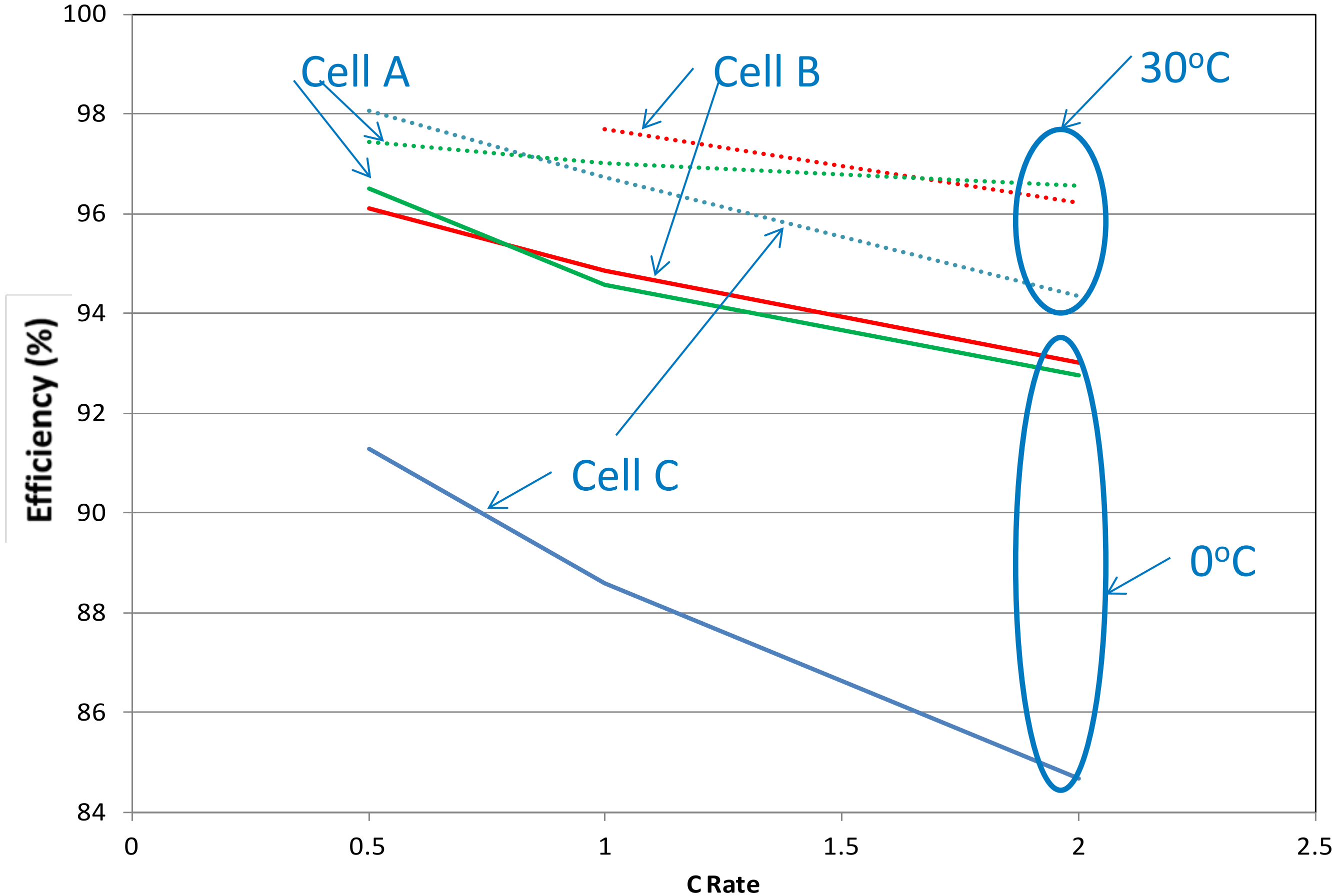
- Continue thermal characterization for DOE, USABC, and partners
  - Cell, module, and subpack calorimeters are available for industry validation of their energy storage systems.
- Develop battery usage models with the calorimeter heat generation data that will predict the thermal performance of energy storage systems under various drive cycles and environmental conditions—models to be utilized by Fiat-Chrysler, Ford, GM 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

- NREL 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
  - Data has been shared with the battery developers to improve their designs
  - Developed innovative thermal management strategies in partnership with the battery manufacturers
  - Identified additives and cell architecture that improved the high and low temperature performance of the cell.
- Thermal properties are used for the thermal analysis and design of improved battery thermal management systems to support and achieve life and performance targets.

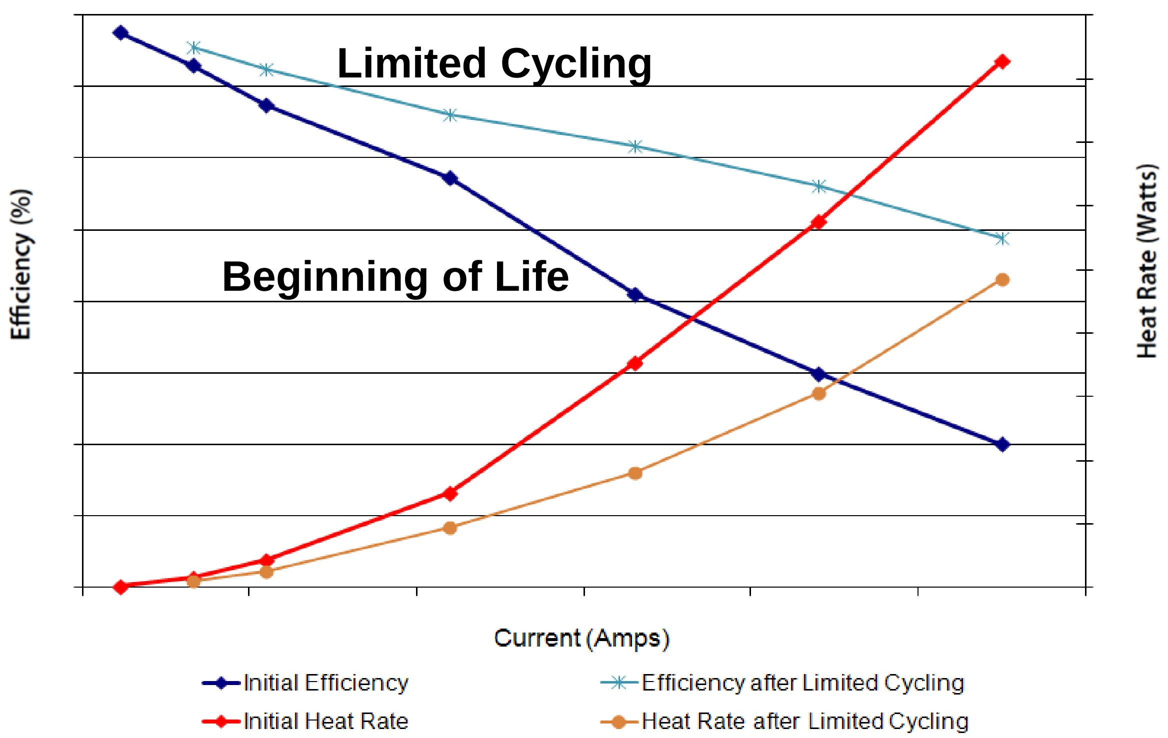
Technical Back-Up Slides

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.

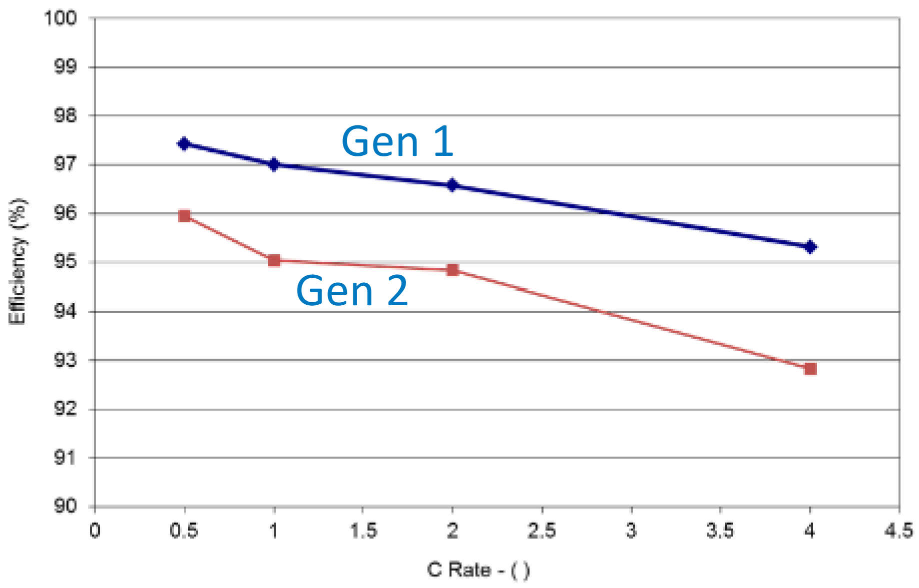
Efficiency Can Change After Limited Battery Use



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.

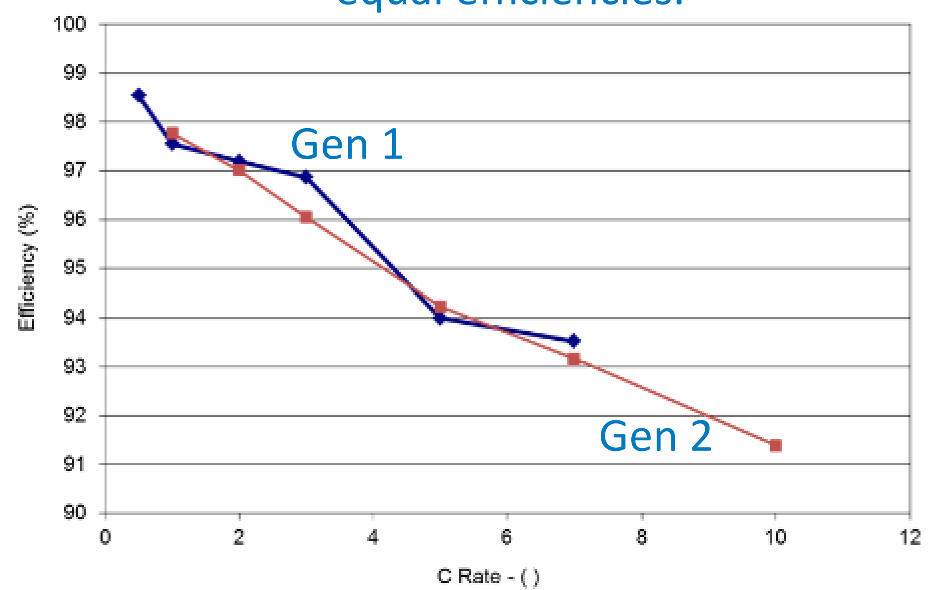
Efficiency Comparison of Successive Generations of Cells



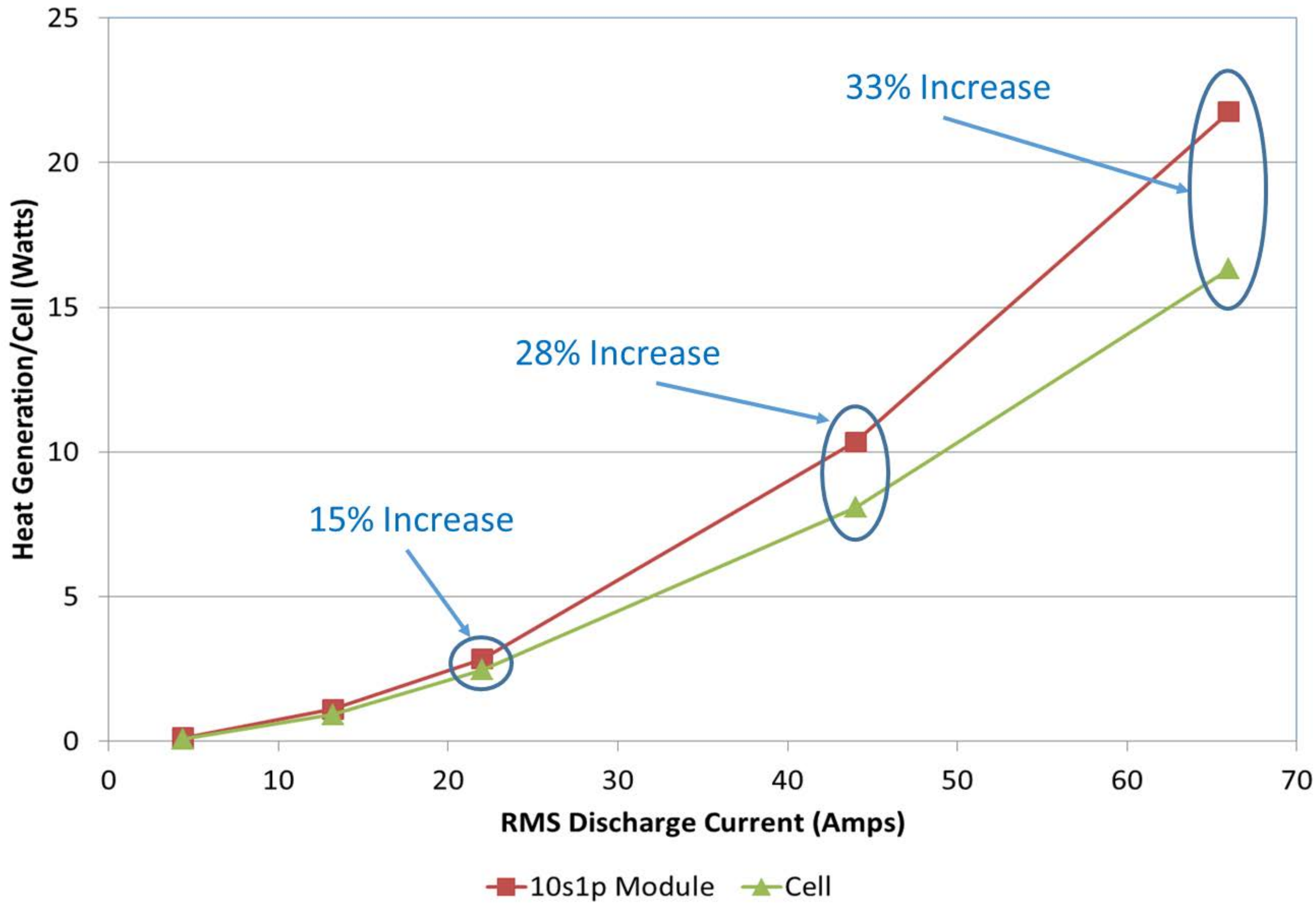
Full Discharge – 100% to 0% SOC: Testing over the entire discharge range of the cell gives the impression that the second-generation cell is less efficient.

It is 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.



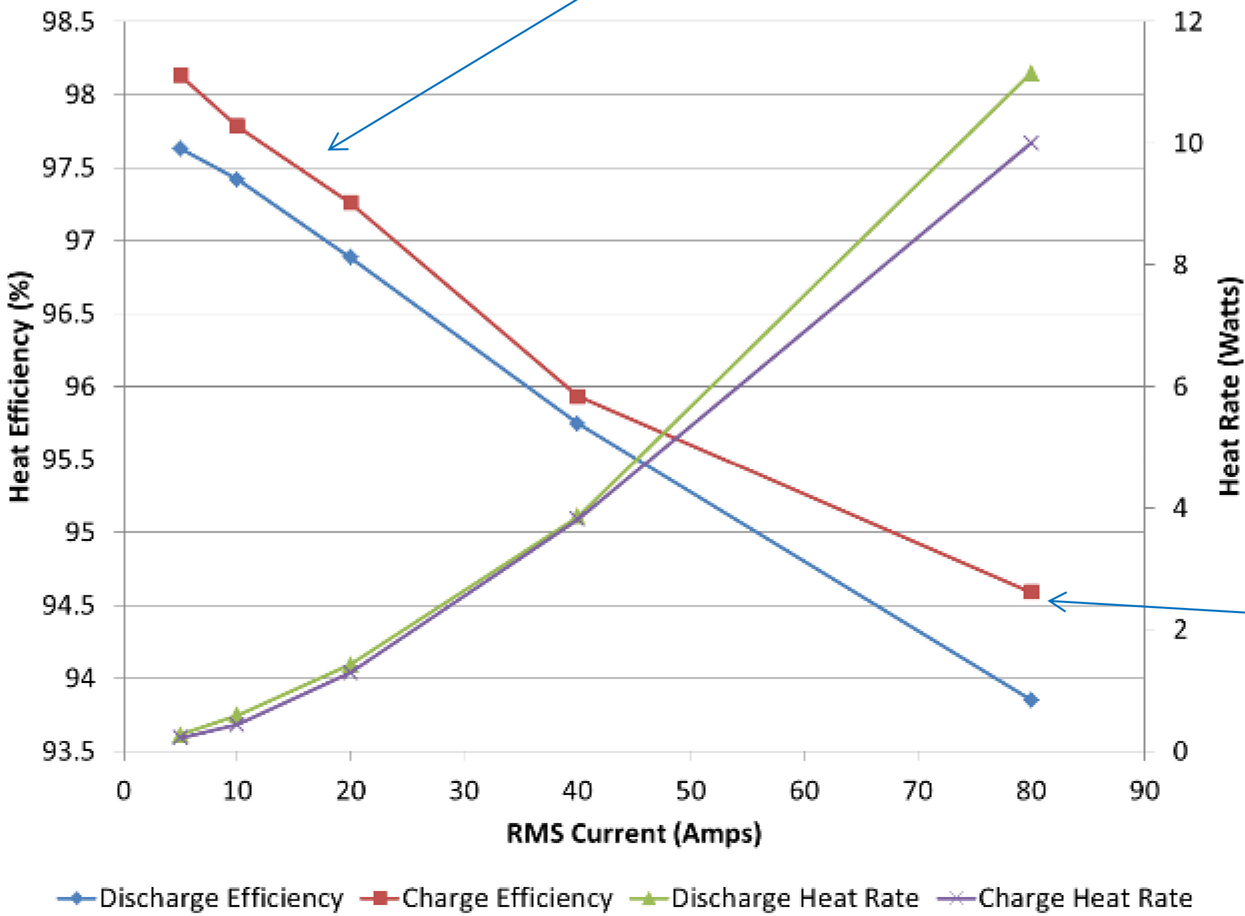
Cell versus Module Heat Generation



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