NATIONAL RENEWABLE ENERGY LABORATORY

Battery Thermal Characterization

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DOE Vehicle Technologies Office
2018 Annual Merit Review and Peer Evaluation Meeting

Project ID # BAT204

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 for FY 2017: $600k
- Funding for FY 2018: $300k

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
- 24M
- Saft
- Amprius
- 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
9/2017	Milestone	Report on thermal evaluation of advanced cells and battery packs	Complete
12/2017	Milestone	Present thermal data at USABC technical review meetings	Complete
3/2018	Milestone	Report on battery thermal data for USABC cells during first half of FY17	Complete
6/2018	Milestone	Present at Annual Merit Review	On Track
9/2018	Milestone	Report on battery thermal data collected on USABC battery cells/packs for FY18	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

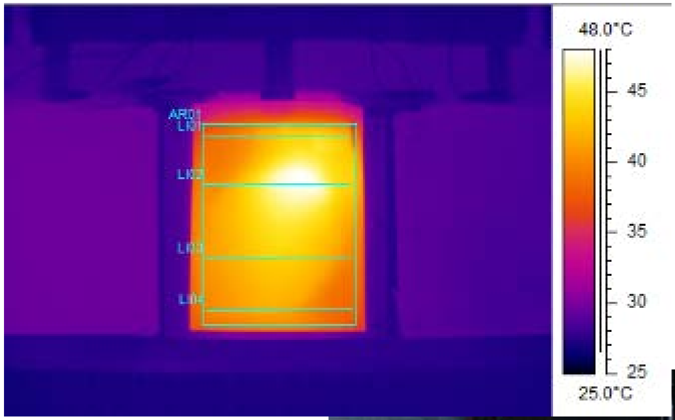
- NREL provides critical thermal data to the battery manufacturers and OEMs that can be used to improve the design of the cell, module, and pack and their respective thermal management systems.
- The provided data include infrared imaging results and heat generation of cells under typical profiles for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

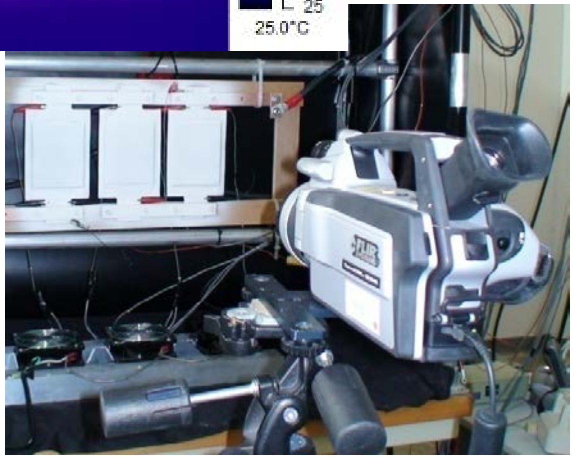
EV = electric vehicle; HEV = hybrid electric vehicle; OEM = original equipment manufacturer; PHEV = plug-in hybrid electric vehicle; HWFET = Highway Fuel Economy Test; UDDS = Urban Dynamometer Driving Schedule

Approach – Thermal Testing

Thermal Imaging

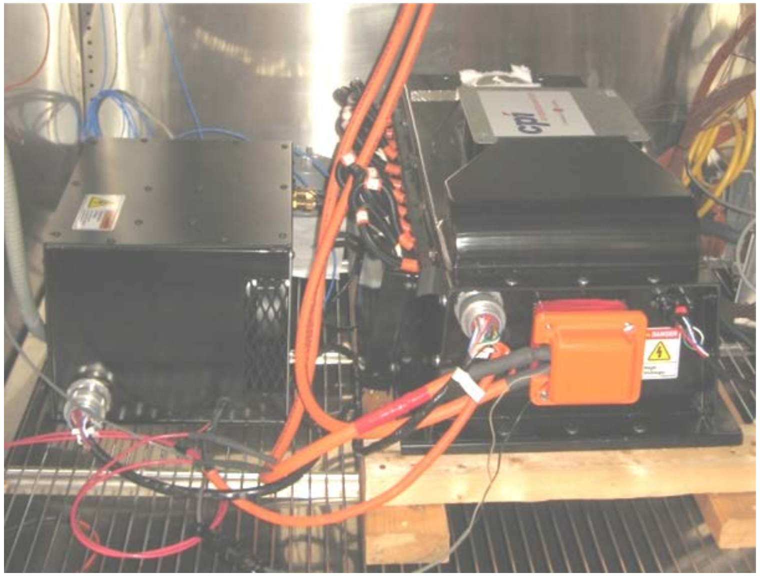
- **Temperature variation** across cell
- Profiles: US06 cycles, CC discharge/charge
- Unique non-destructive testing method to identify thermal areas of concern





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

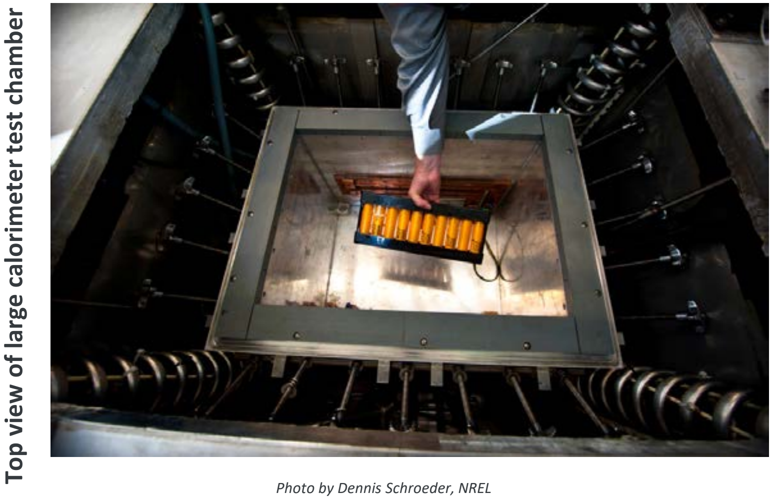
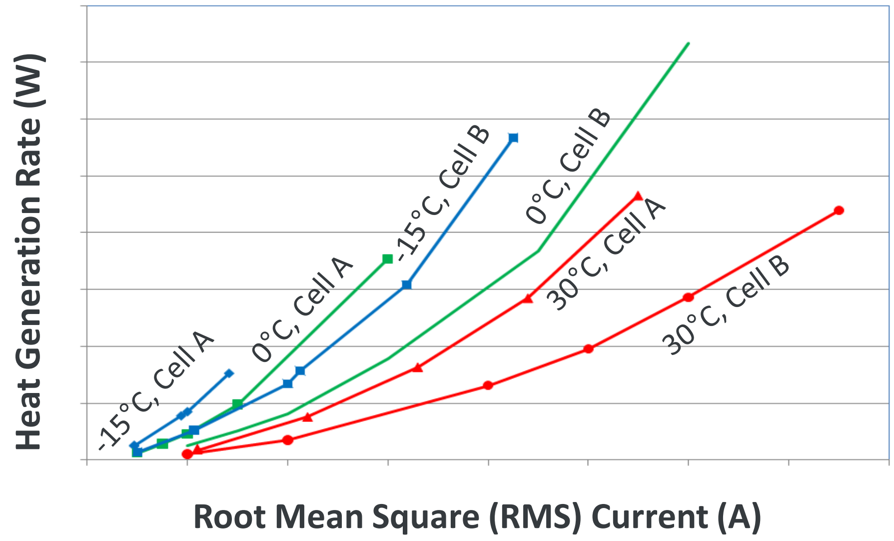
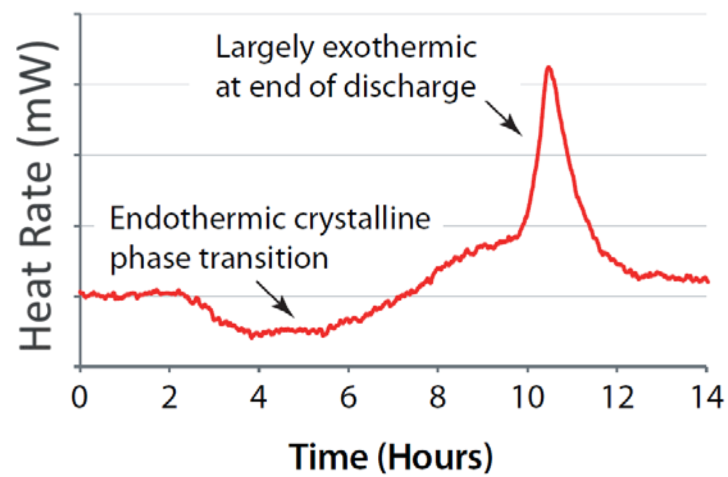


Photo by Dennis Schroeder, NREL



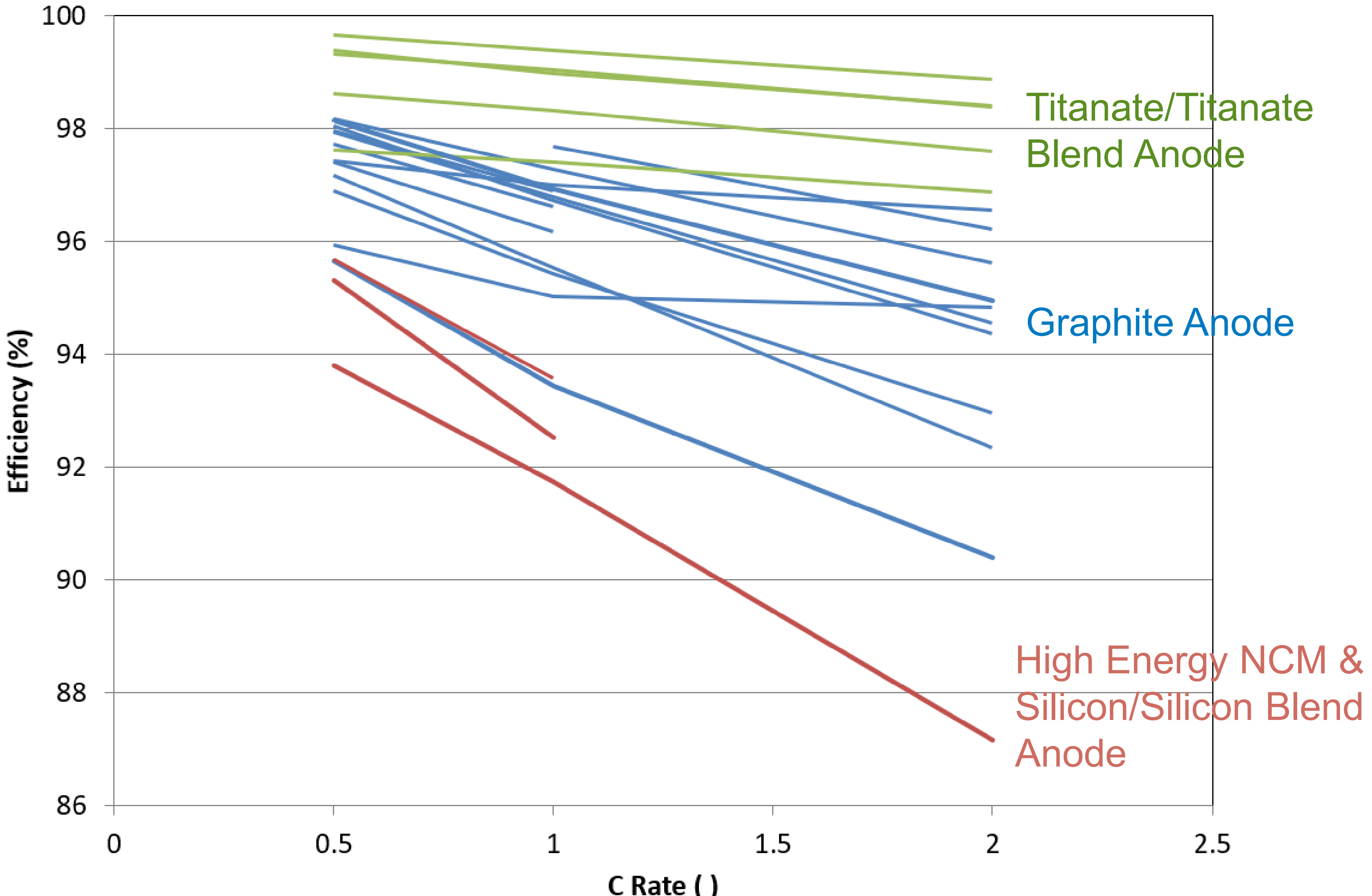
- **Heat generation**, heat capacity**,** and efficiency
- Test temperature range: -30°C to +45°C
- Profiles: USABC and US06 cycles, CC

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



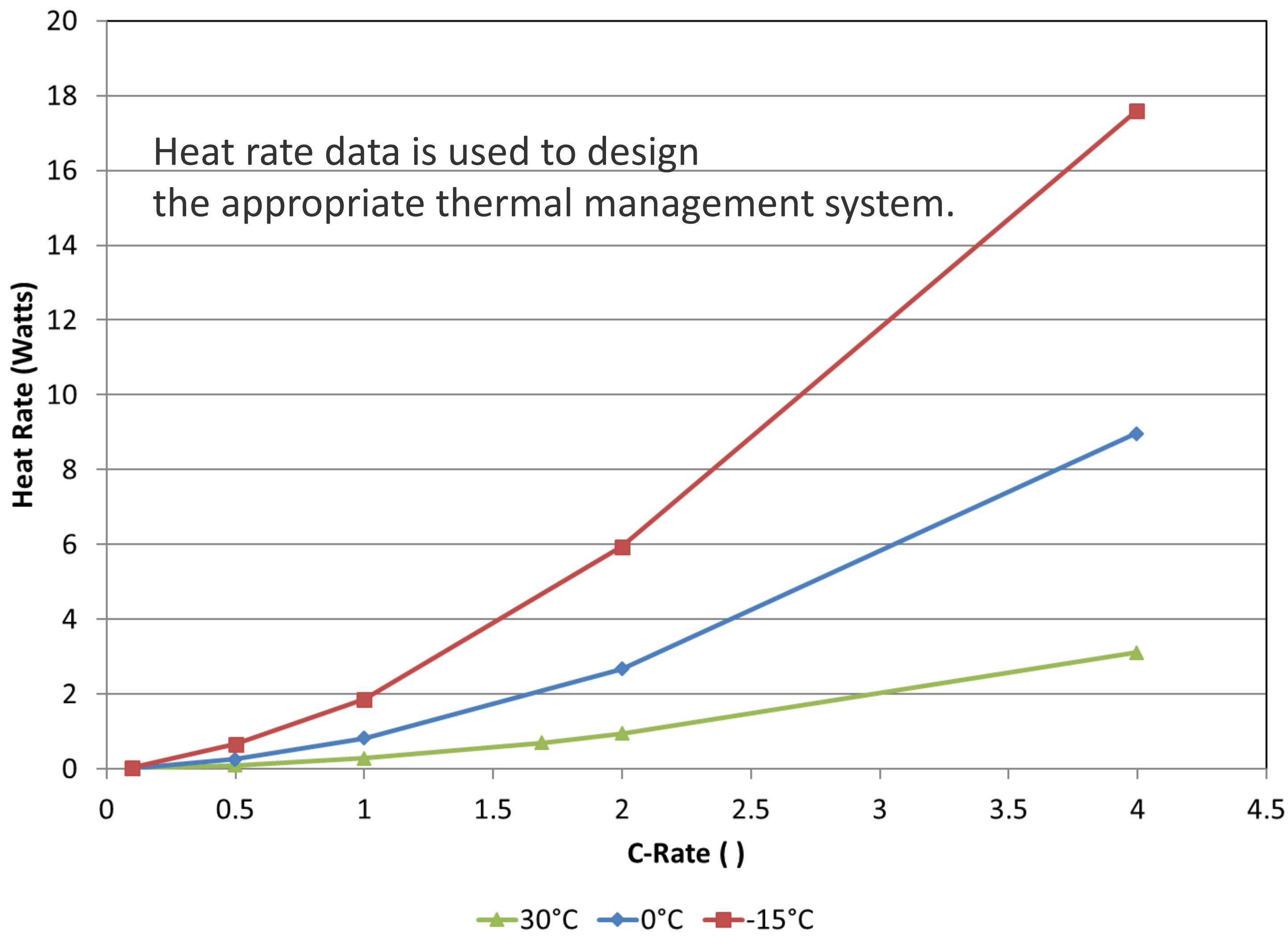
Efficiency Comparison of Cells

Technical Accomplishments



Calorimeter Heat Rate as a function of Temperature

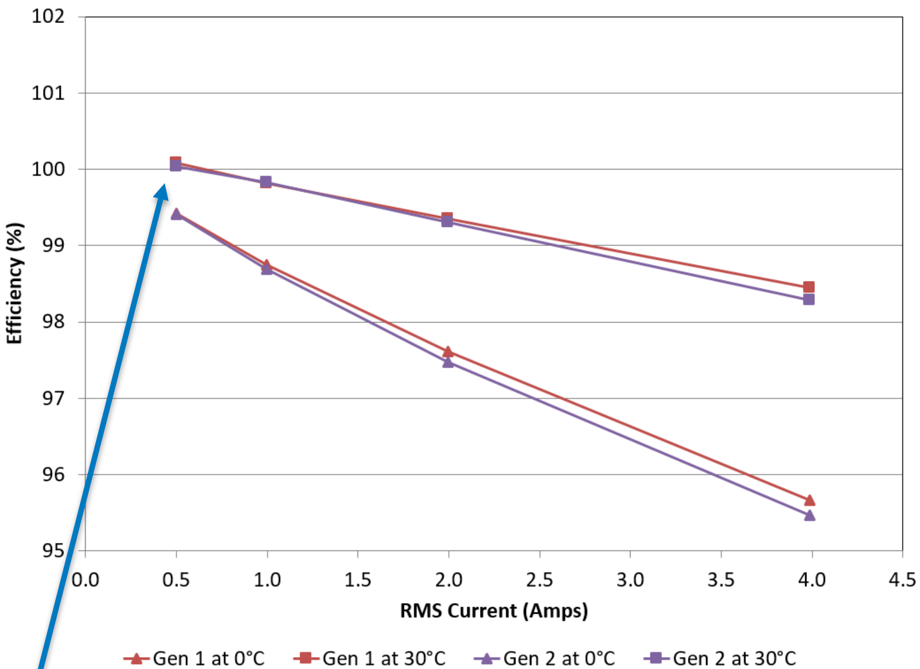
Technical Accomplishments



Efficiency Varies as a Function of SOC

Technical Accomplishments

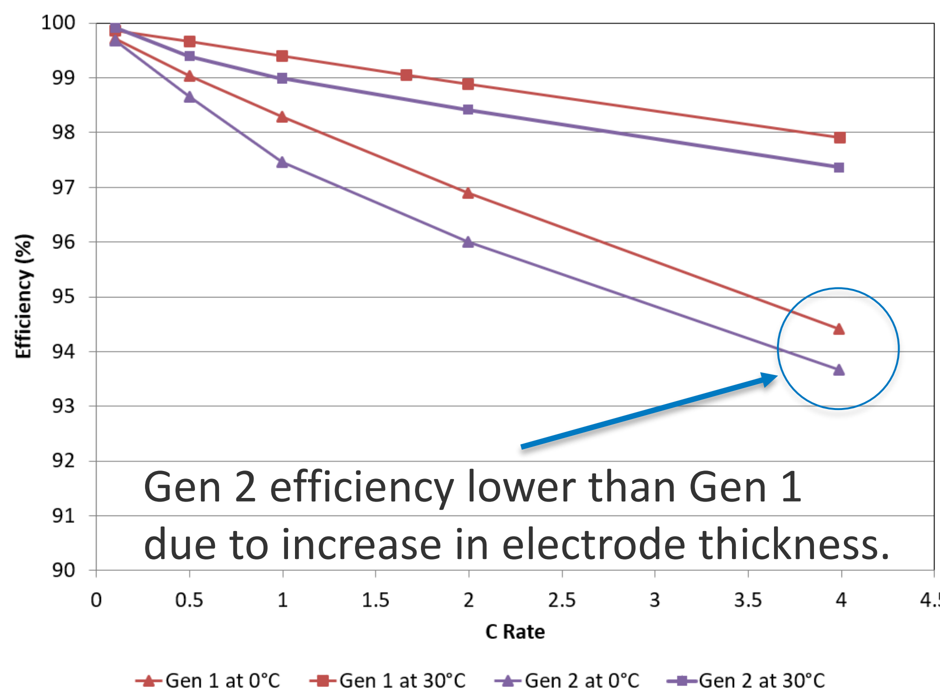
Partial discharge: 95% SOC ⇔ 20% SOC



Heat Efficiency at low rates affected by entropic (endothermic) chemical response.

Spread in efficiencies between the two generations of cells under full charge is due to high impedance at SOC extremes. Behavior not exhibited under partial discharge tests.

Full discharge: 100% SOC ⇔ 0% SOC

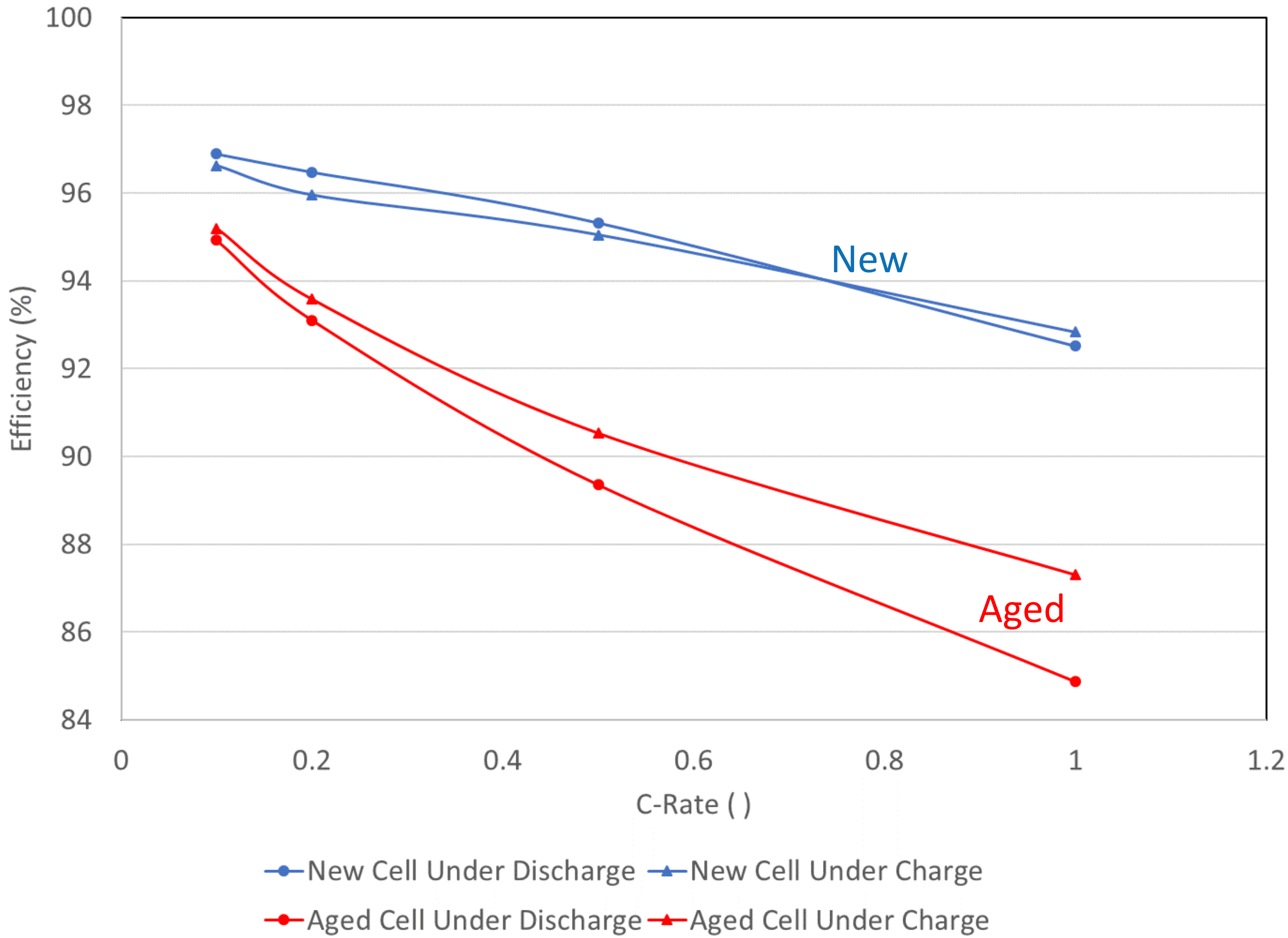


Gen 2 efficiency lower than Gen 1 due to increase in electrode thickness.

SOC: State-of-Charge

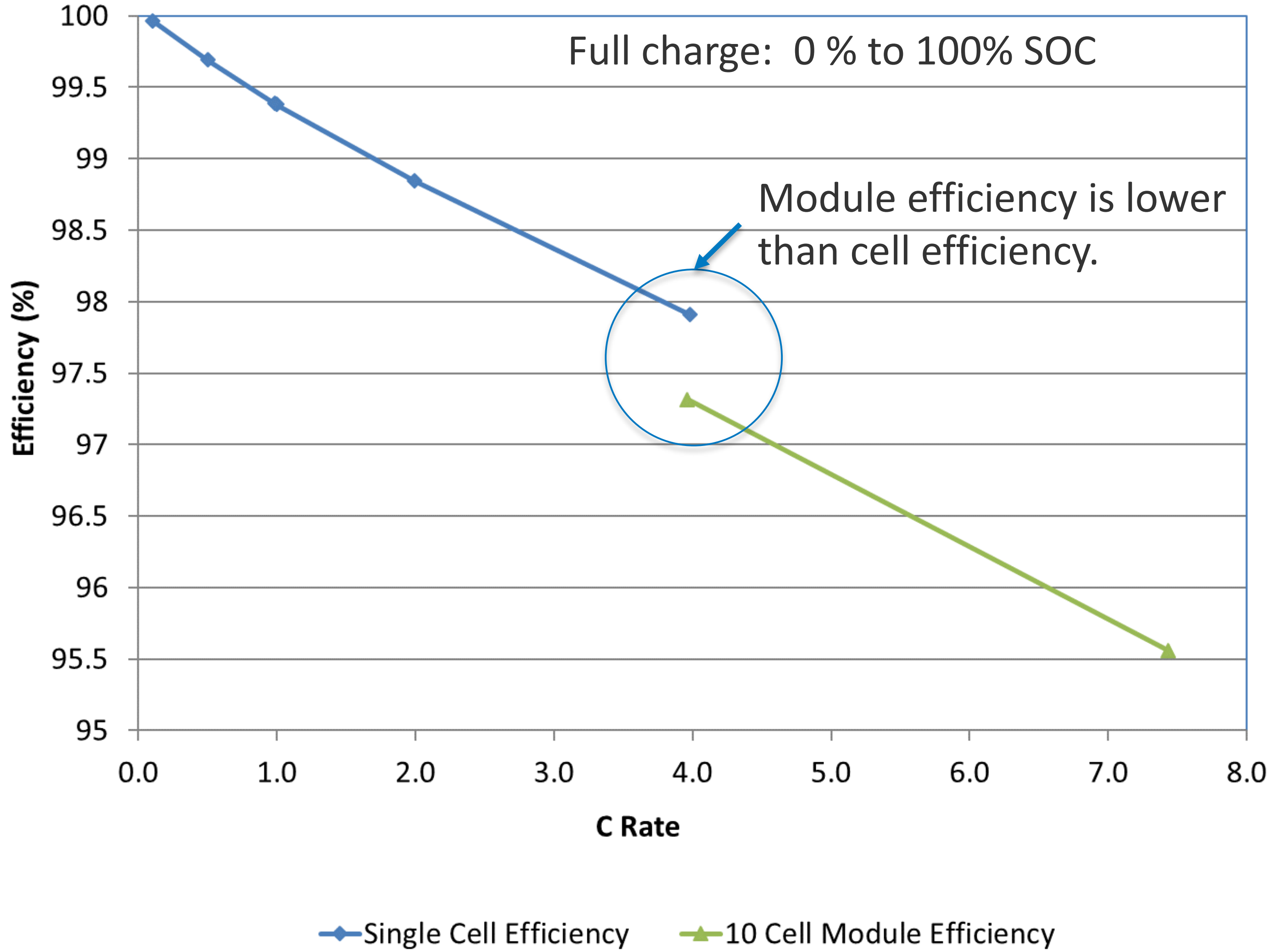
Limited Cycling affects Efficiency of Silicon Blended Anodes

Technical Accomplishments



Module Efficiencies Suffer due to Interconnects

Technical Accomplishments



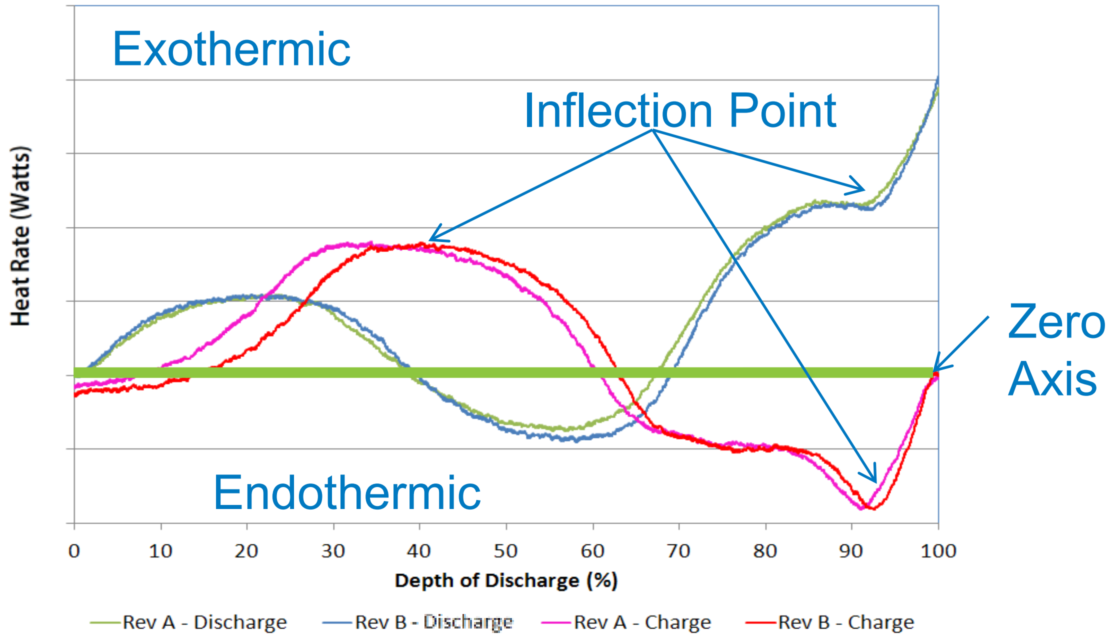
Low-Current Entropic Heating

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.

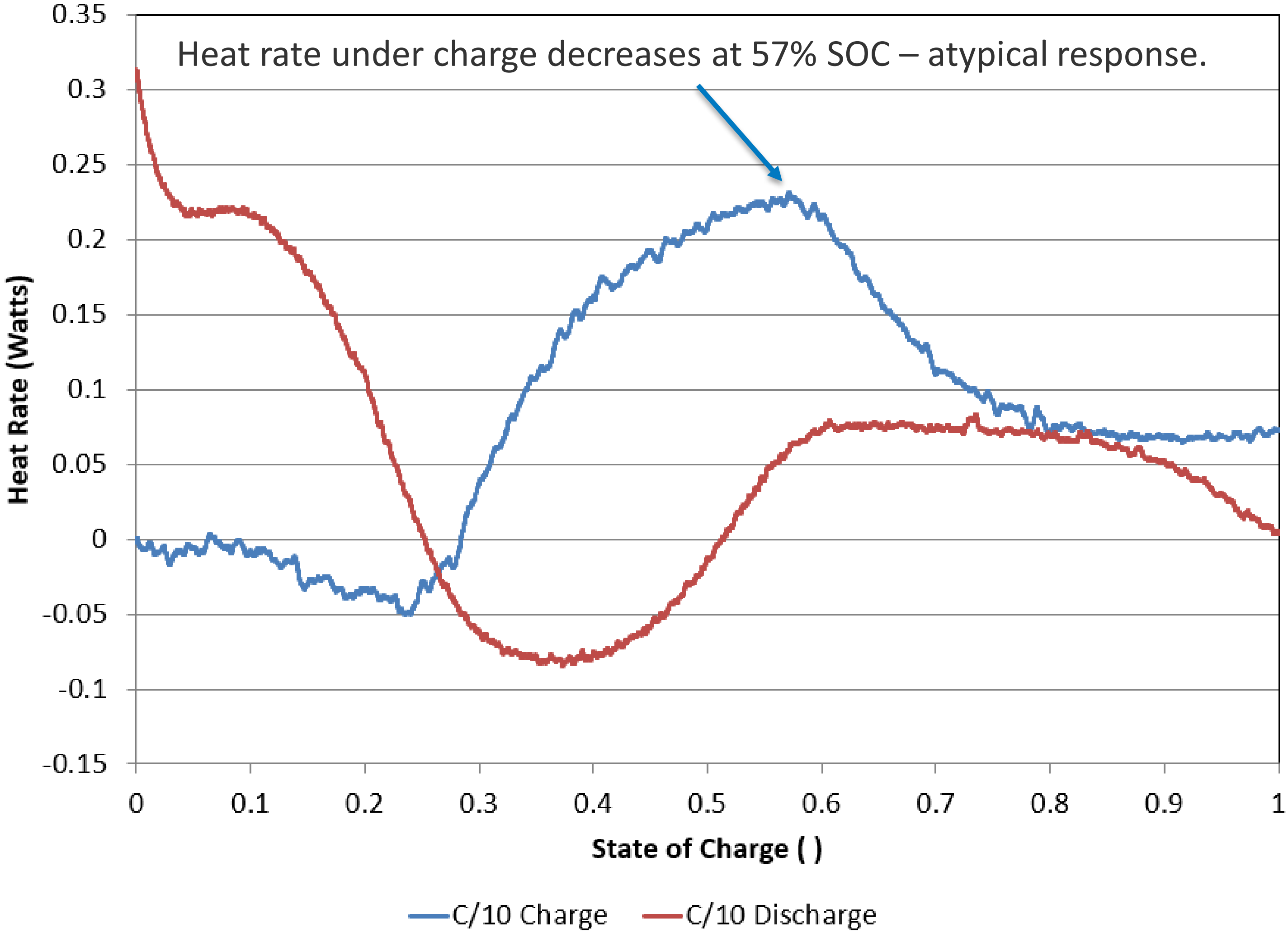
Cycling the battery at the inflection points may cause cracks in the anode or cathode, which may lead to decreased performance and life.



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

Entropic Testing of High Nickel Content NMC

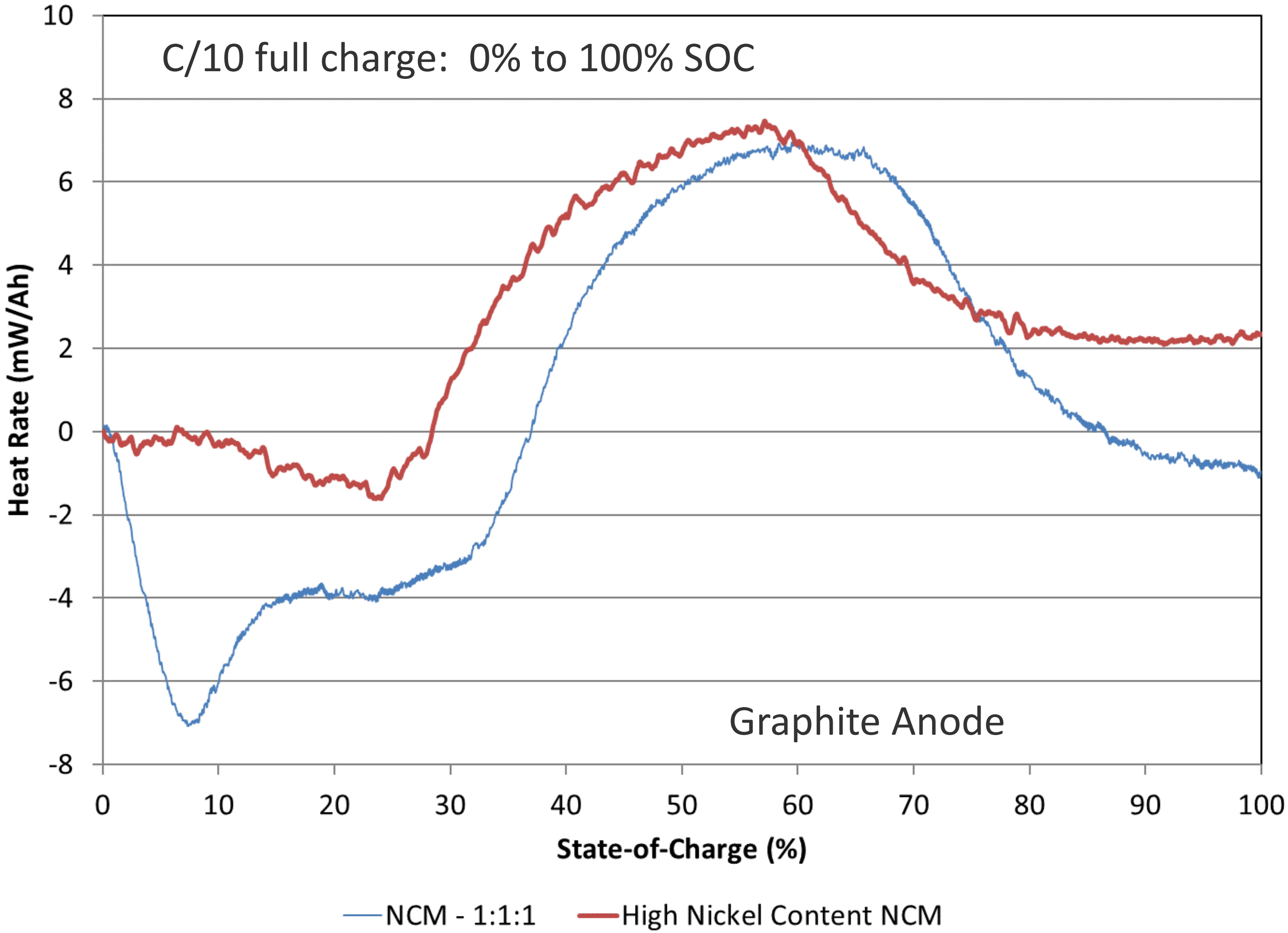
Technical Accomplishments



NMC: Nickel, Manganese, Cobalt

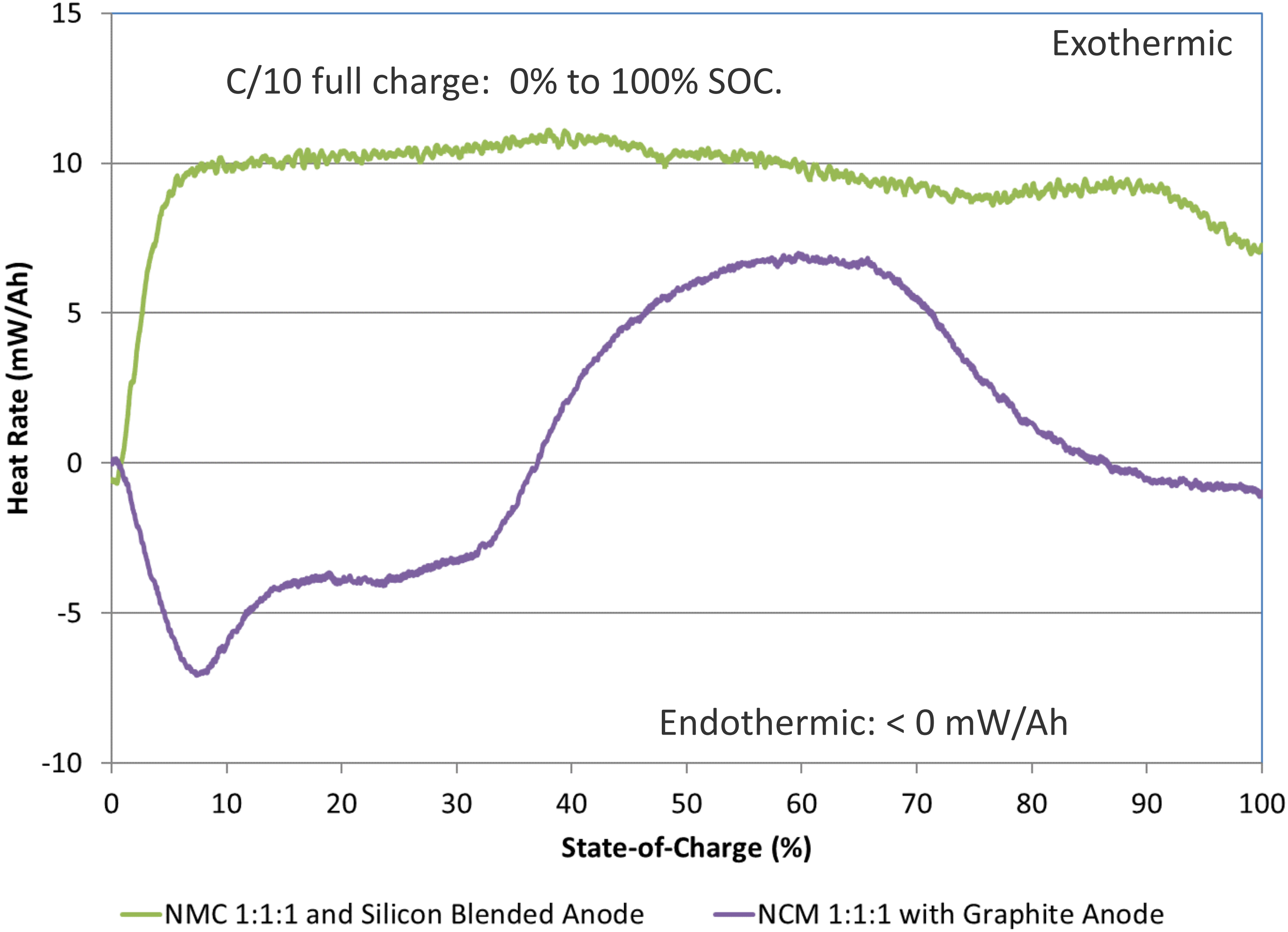
Entropic Signature Comparison of Different NCMs

Technical Accomplishments



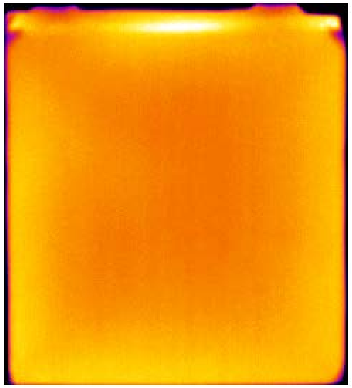
Entropic Study: Silicon Blended Anodes do not Exhibit Phase Changes

Technical Accomplishments

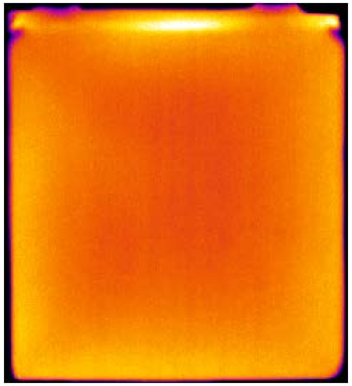


Infrared Image at End of Constant Current Discharge

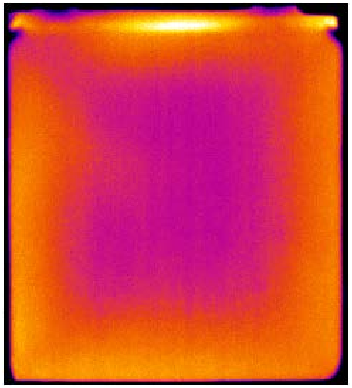
Technical Accomplishments



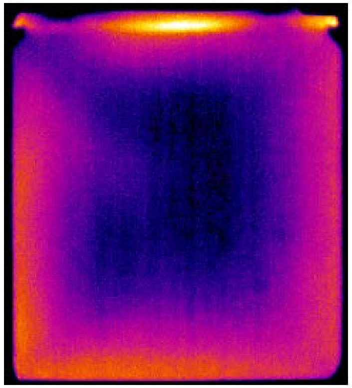
Δ Temp Spread



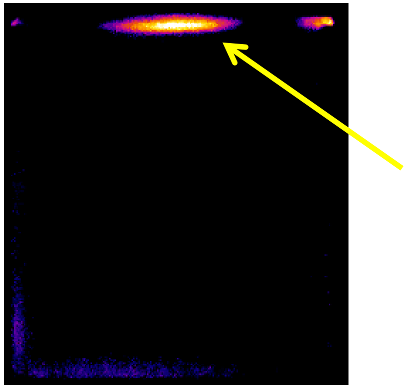
Δ Temp Spread - n°C



Δ Temp Spread – 2n°C



Δ Temp Spread – 3n°C



Δ Temp Spread – 4n°C

Heat being generated at tab connections

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

Responses to Previous Year Reviewers' Comments

- Reviewer Comment: Suggest that it would be useful for DOE to consider engaging NREL with ongoing projects at an earlier stage (i.e., understanding the thermal performance in smaller cells and during the cell design process)
- Presenter Reply: NREL has developed a suite of calorimeters – micro to macro. NREL's micro-calorimeter would be ideal for testing cathode and anode half cells as well as down selecting materials during the initial stages of development. The calorimeters can also be used to identify beneficial additives and cell architectures.

Responses to Previous Year Reviewers' Comments

- Reviewer Comment: The focus on incorporating modeling with experimental data has been a nice evolution of this program. It would be interesting to see more solid electrolyte cell testing and studies. It would also be useful for DOE to consider engaging NREL with ongoing projects at an earlier stage (i.e., understanding the thermal performance in smaller cells and during the cell design process).
- Presenter Reply: NREL has started testing the high energy NCM cathodes as well as one solid electrolyte cell. The calorimeter technology can be applied to the new cathode and anode materials being developed – lithium-sulfur, lithium metal, sodium metal, silicon, etc…

Collaboration and Coordination with Other Institutions

- United States Advanced Battery Consortium (USABC) – Fiat-Chrysler, Ford, GM
- USABC Contractors – Technologies evaluated at NREL
  - LGCPI
  - 24M
  - Saft
  - Amprius
  - Envia
  - Farasis
- 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 targeting a 15-year lifespan
- Understand and address issues related to extreme fast charging
- 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.
  - Obtained heat capacity and heat generation of cells under various power profiles
  - Obtained thermal images of the cells under various drive cycles
  - Used the measured results to validate our thermal models
  - Shared data 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.

Thank You

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Publication Number

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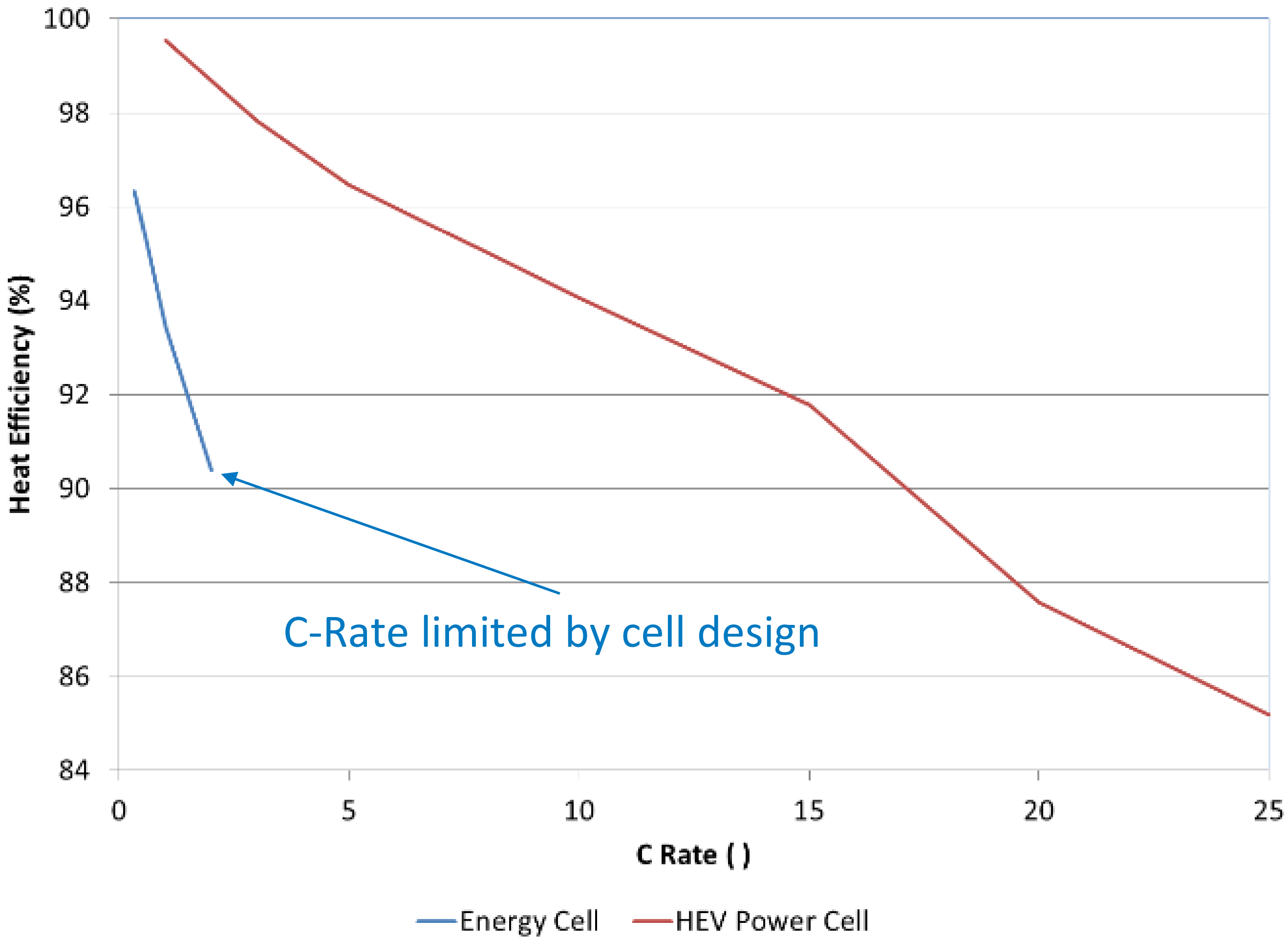
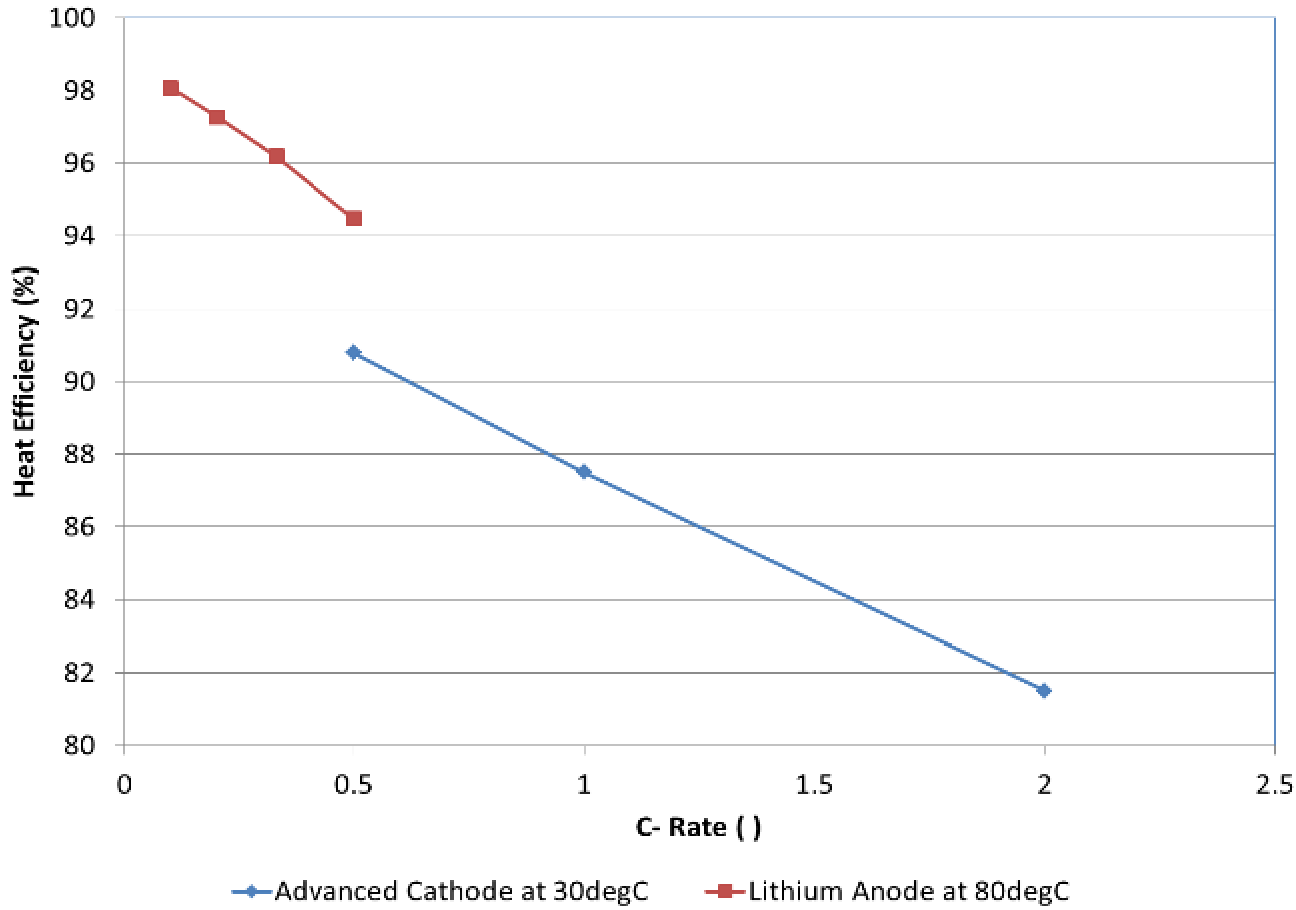
Technical Back-Up Slides

Discharge Efficiency Comparison of Energy and Power Cells



HEV: hybrid electric vehicle

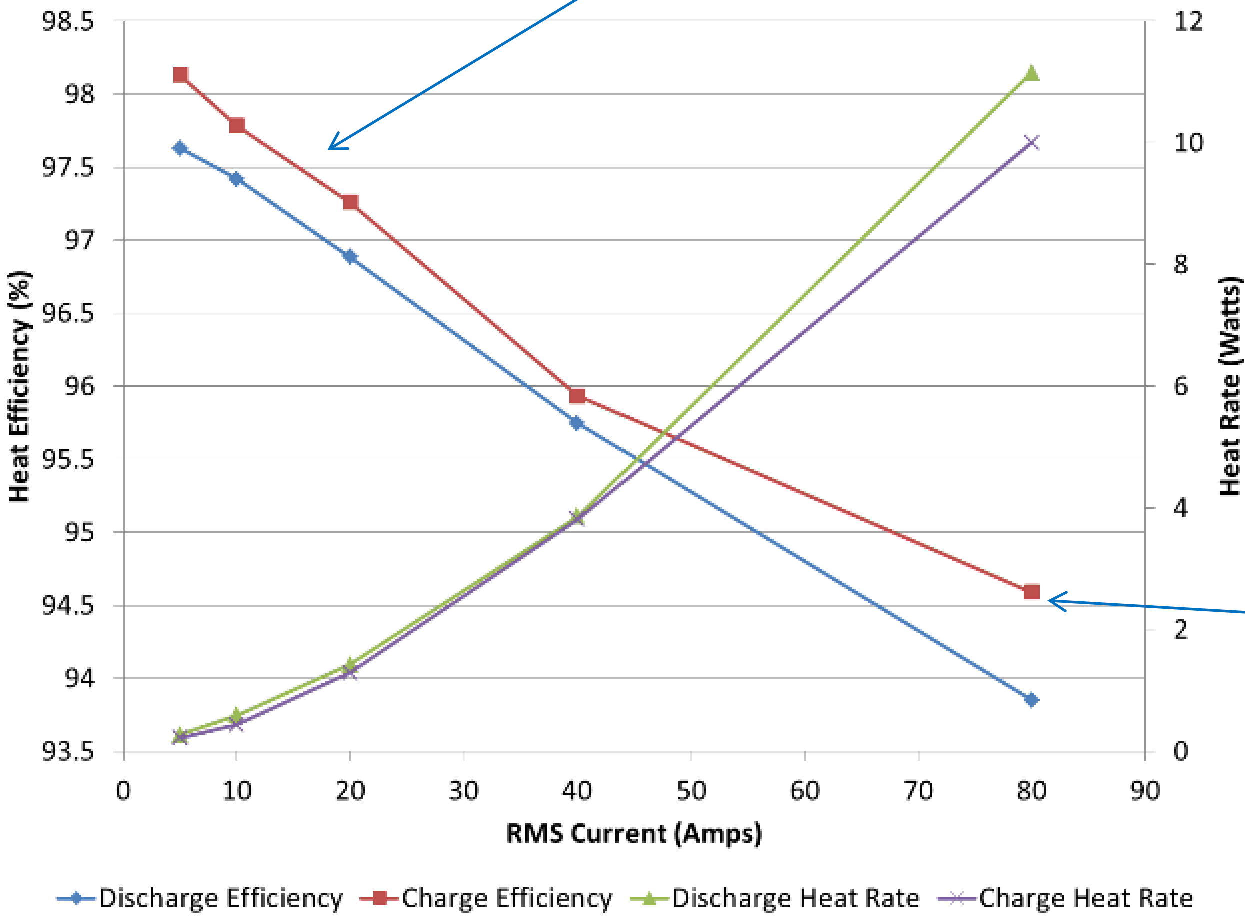
Efficiency Limitations Associated with Advanced Chemistries



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

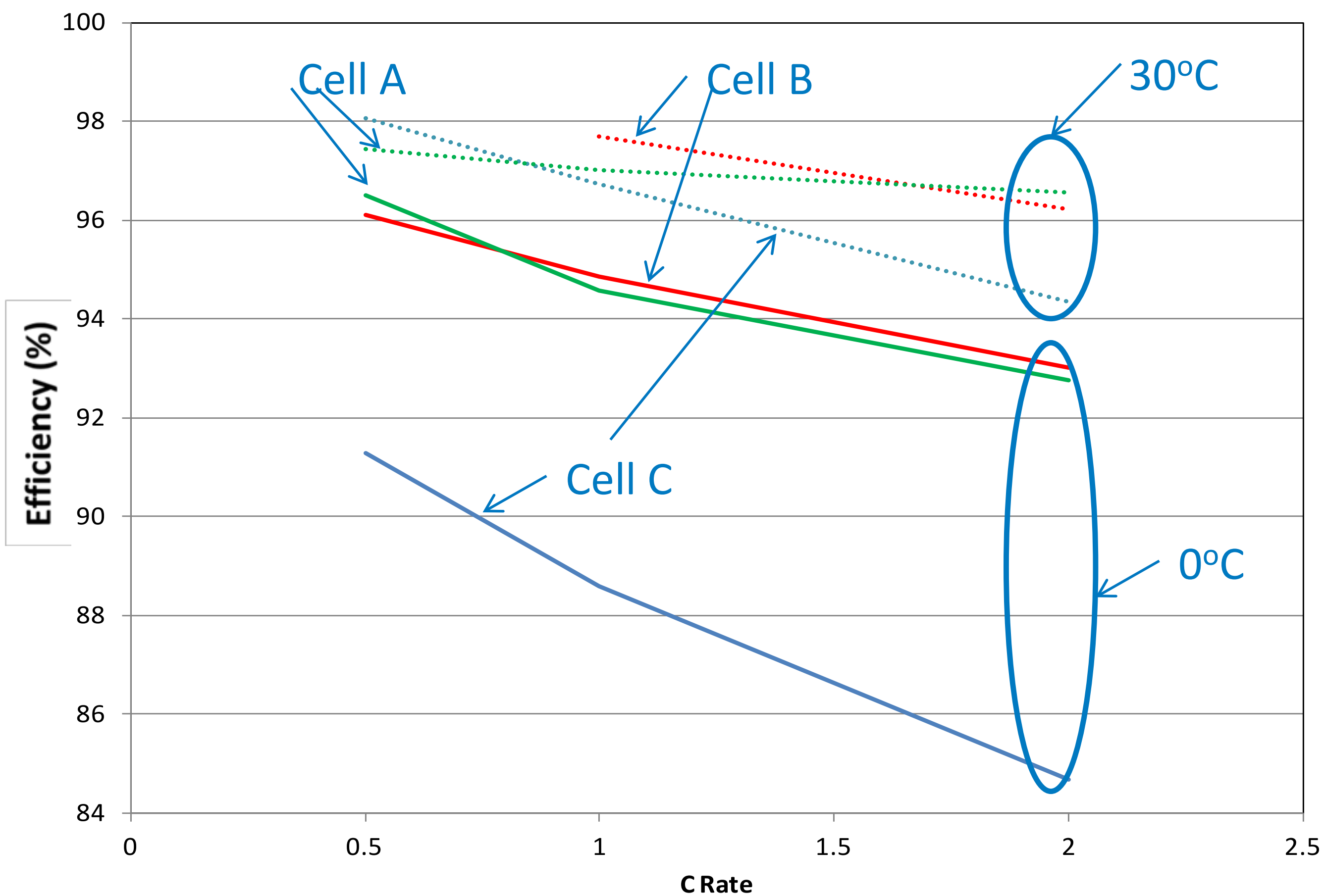
New Chemistries – Titanate Anodes

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



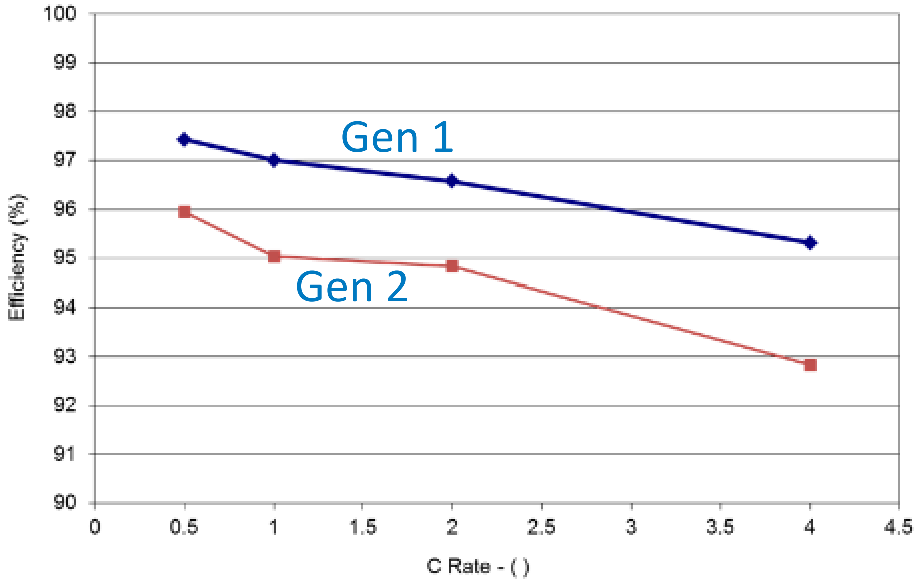
Charge impedance limiting Ah input at high rates

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.

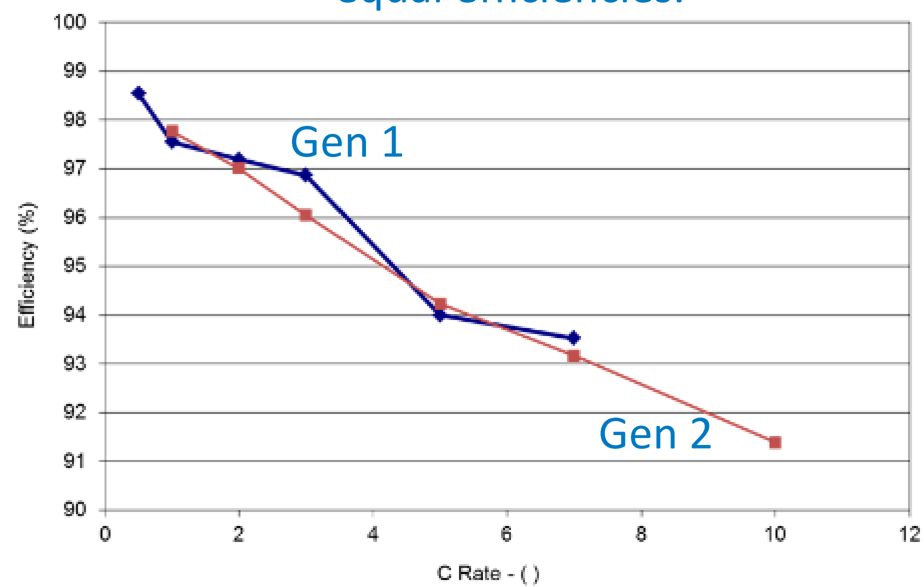
Efficiency Comparison of Successive Generations of Cells



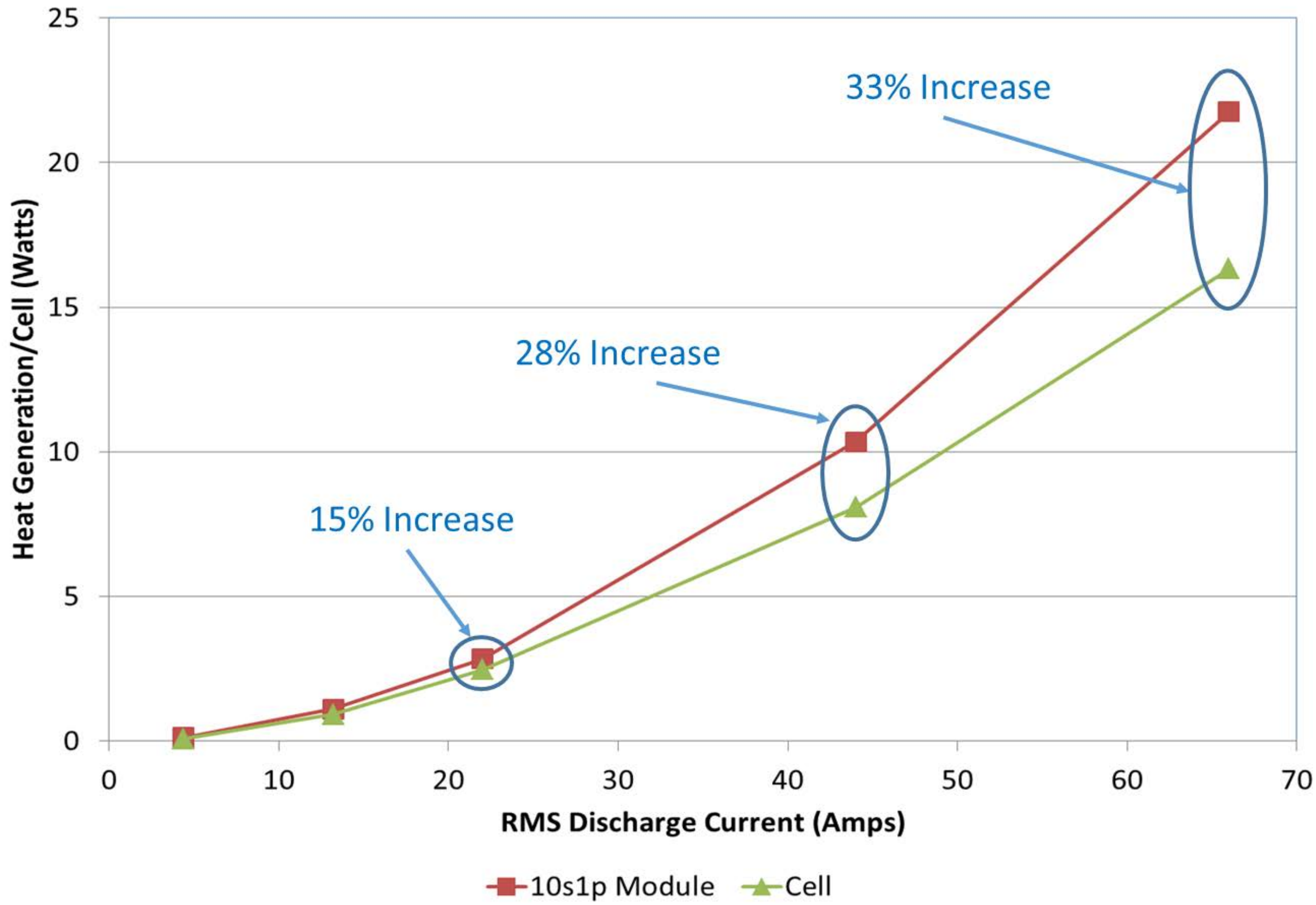
Full Discharge – 100% to 0% SOC: Testing over the entire discharge range of the cell gives the impression that the second-generation cell is less efficient.

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.