Battery Thermal Characterization

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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 measured results to validate thermal models
  - Data have been shared with 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

OVERVIEW

Timeline

- Project Start Date: October 2004
- Project End Date: September 2018
- Percent Complete: Ongoing

(Supporting ongoing DOE/USABC battery developments)

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

RELEVANCE

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

Objectives

- 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
- Enhance and validate physics-based models to support the thermal design of long-life, low-cost energy storage systems
- Quantify the impacts of temperature and duty cycle on energy storage system life and cost

APPROACH

Cells, Modules, and Packs

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

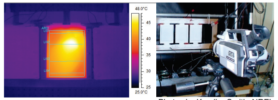
Test Profiles
- Normal operation
- Aggressive operation
- Driving cycles
  - US06
  - UDDS
  - HWFET
- Discharge/charge rates
  - Constant current (CC)
  - Geometric charge/discharge
  - FreedomCAR profiles

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 battery manufacturers and OEMs that can be used to improve the design of cells, modules, packs, and their respective thermal management systems
- Data include infrared imaging results and heat generation of cells under typical profiles for HEV, PHEV, and EV applications

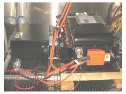
Cell-Level Testing

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



Photos by Kandler Smith, NREL

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



Heat Generation and Efficiency

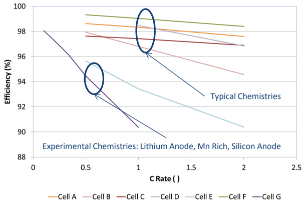
Using state-of-the-art isothermal battery calorimeters
- Heat generation, heat capacity, and efficiency
- Test Temperature Range: -30ºC to +45ºC
- Profiles: USABC and US06 cycles, CC

Top view of large calorimeter test chamber
Photo by Dennis Schroeder, NREL

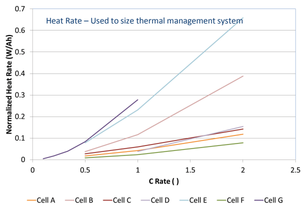
Specifications	Cell Calorimeter	Module Calorimeter	Pack Calorimeter
Maximum Voltage (Volts)	50	500	600
Sustained Maximum Current (Amps)	250	250	450
Excursion Currents (Amps)	300	300	1000
Volume (liters)	9.4	14.7	96
Maximum Dimensions (cm)	30.5 x 20.3 x 15.2	35 x 21 x 20	60 x 40 x 40
Operating Temperature (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

TECHNICAL ACCOMPLISHMENTS

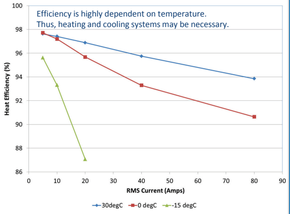
Efficiency Comparison of Cells Tested in FY15 and FY16 at 30°C Under Full Discharge from 100% to 0% SOC



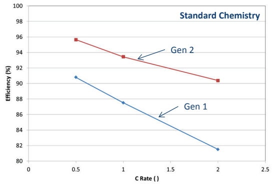
Heat Rate Comparison of Cells Tested in FY15 and FY16 at 30°C Under Full Discharge from 100% to 0% SOC



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



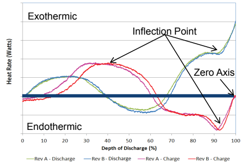
EV Cell Gen1/Gen 2 Efficiency Comparison



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

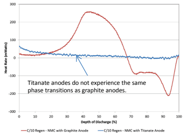
Heat in a cell is produced by:
- Resistance of various cell components (electrode, cathode, anode, etc.); this is known as Joule heating, which can be minimized by cycling cells at low currents
- Entropic reactions within the cell—exothermic and endothermic reactions within the cell due to the transfer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

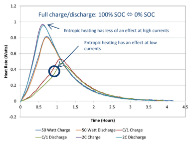
In general, Joule heating is an order of magnitude less than entropic heating

Titanate Anodes Limit Phase Transition

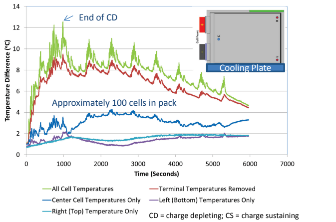


NMC = nickel manganese cobalt

Calorimetry Testing Can Identify Entropic Heating/Cooling



Thermal Management System Performance - PHEV CD/CS Drive Cycle

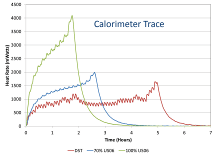


CD = charge depleting; CS = charge sustaining

Test	End of CD Cycle Ambient Temp. (ºC)	End of CD Cycle Maximum Temp. (ºC)	End of CD Cycle Delta Temp. (ºC)	End of CS Cycle Maximum Temp. (ºC)	End of CS Cycle 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 3ºC. In this pack the cell-to-cell temperature difference is greater than 12ºC.
- 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.

Heat Generation under Various Drive Cycles

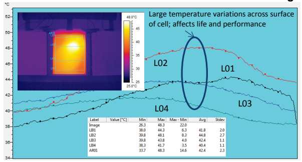


Calorimeter can measure efficiency and heat generation under various drive cycles—helps in designing thermal management systems for battery packs

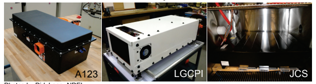
Cycle	RMS Current (amps)	Efficiency (%)	Heat Rate (watts/cell)
DST	4.9	95.3	0.5
70% Power US06	8.0	93.9	1.2
100% Power US06	11.8	91.1	2.6

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

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



Pack Thermal Temperature Studies



Photos by Dirk Long, 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

MILESTONES

Date	Description	Status
9/2015	Report on thermal evaluation of advanced cells and battery packs	Complete
12/2015	Present thermal data at USABC technical review meetings	Complete
3/2016	Report on battery thermal data for USABC cells	Complete
6/2016	Present thermal data at USABC technical review meetings	On Track
9/2016	Report on battery thermal data of USABC battery cells/packs	On Track

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 calorimeter heat generation data that will predict 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)
- Use data 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 energy storage cycle life
- Work with OEMs and battery manufacturers to:
  - Identify best solutions to reduce 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 phase change material, new refrigerants, etc.

COLLABORATION AND ACKNOWLEDGEMENTS

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- Contractors—JCI, Leyden, LGCPI, Maxwell, Saft, SK Innovation, Seeo

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