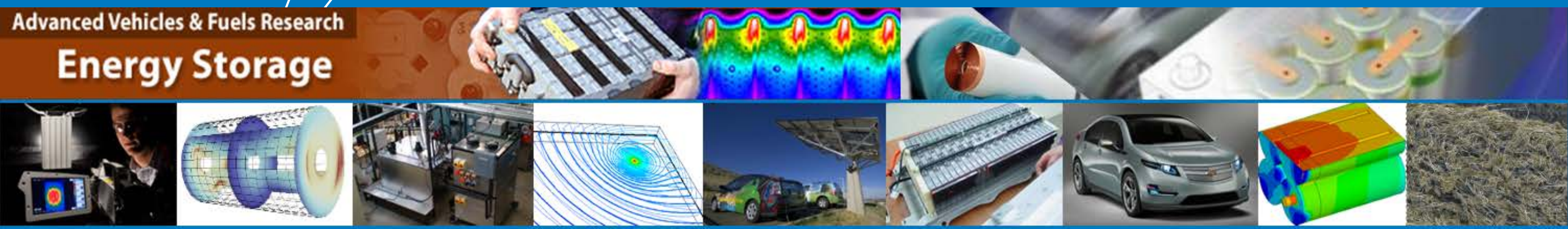
NATIONAL RENEWABLE ENERGY LABORATORY

Battery Thermal Characterization



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National Renewable Energy Laboratory
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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

Timeline

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

Budget

- **Total Project Funding:**
  - DOE Share: 100%
  - Contractor Share: 0%
- **Funding Received in FY13: $600K**
- **Funding for FY14: $535K**

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
- ActaCell
- Cobasys
- Envia
- Farasis
- JCI
- Leyden
- LGCPI
- Maxwell
- Quallion
- 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/US Drive, USABC, and battery developers for improved designs.
- To enhance and validate physics-based models to support the 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

Milestones

Month/ Year	Milestone or Go/No-Go Decision	Description	Status
3/2013	Milestone	Perform thermal evaluation of advanced cells and battery packs	Complete
9/2013	Milestone	Perform thermal evaluation of advanced cells and battery packs	Complete
12/2013	Milestone	Present thermal data at USABC technical review meetings	Complete
3/2013	Milestone	Report on battery thermal data for USABC cells.	Complete
6/2013	Milestone	Present thermal data at USABC technical review meetings	On Track
9/2013	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
  - HWY
- Discharge/charge rates
  - Constant current
  - 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.**

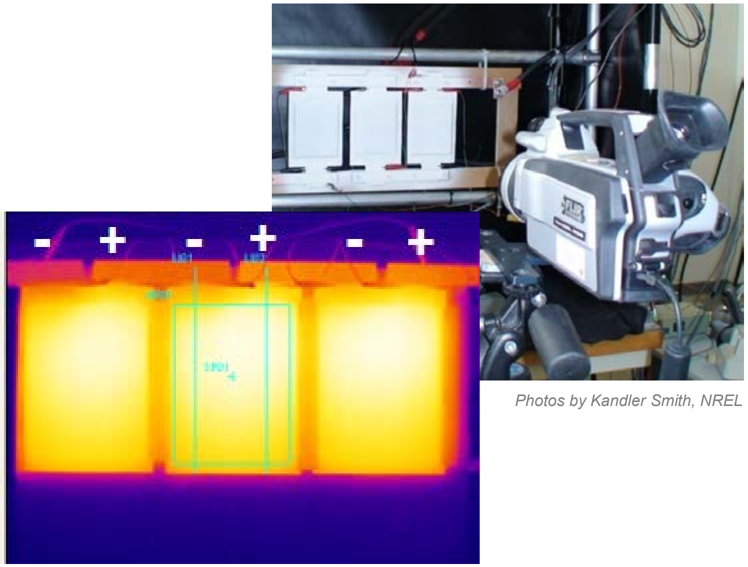
UDDS = Urban Dynamometer Driving Schedule; OEM = original equipment manufacturer; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; EV = electric vehicle

Thermal Testing – Approach

Cell-Level Testing

Thermal Imaging

- **Temperature variation** across cell
- Profiles: US06 cycles, CC discharge

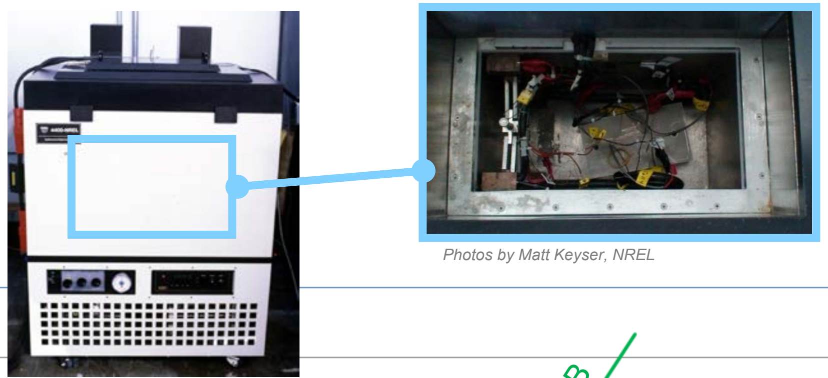


Photos by Kandler Smith, NREL

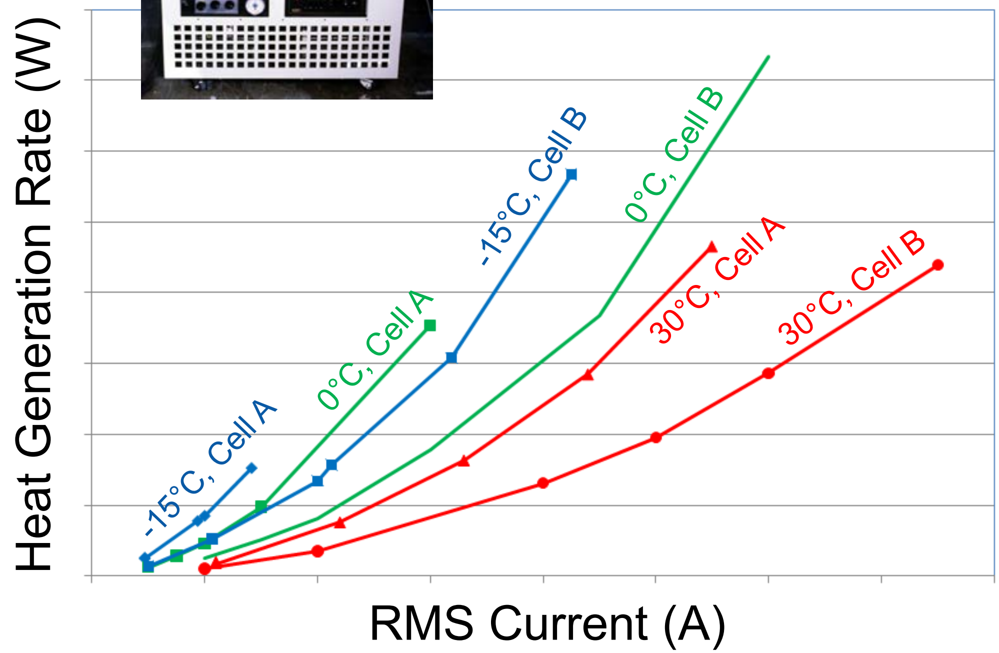
- Results reported to DOE, USABC, and developers

Large-Cell Calorimetry

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

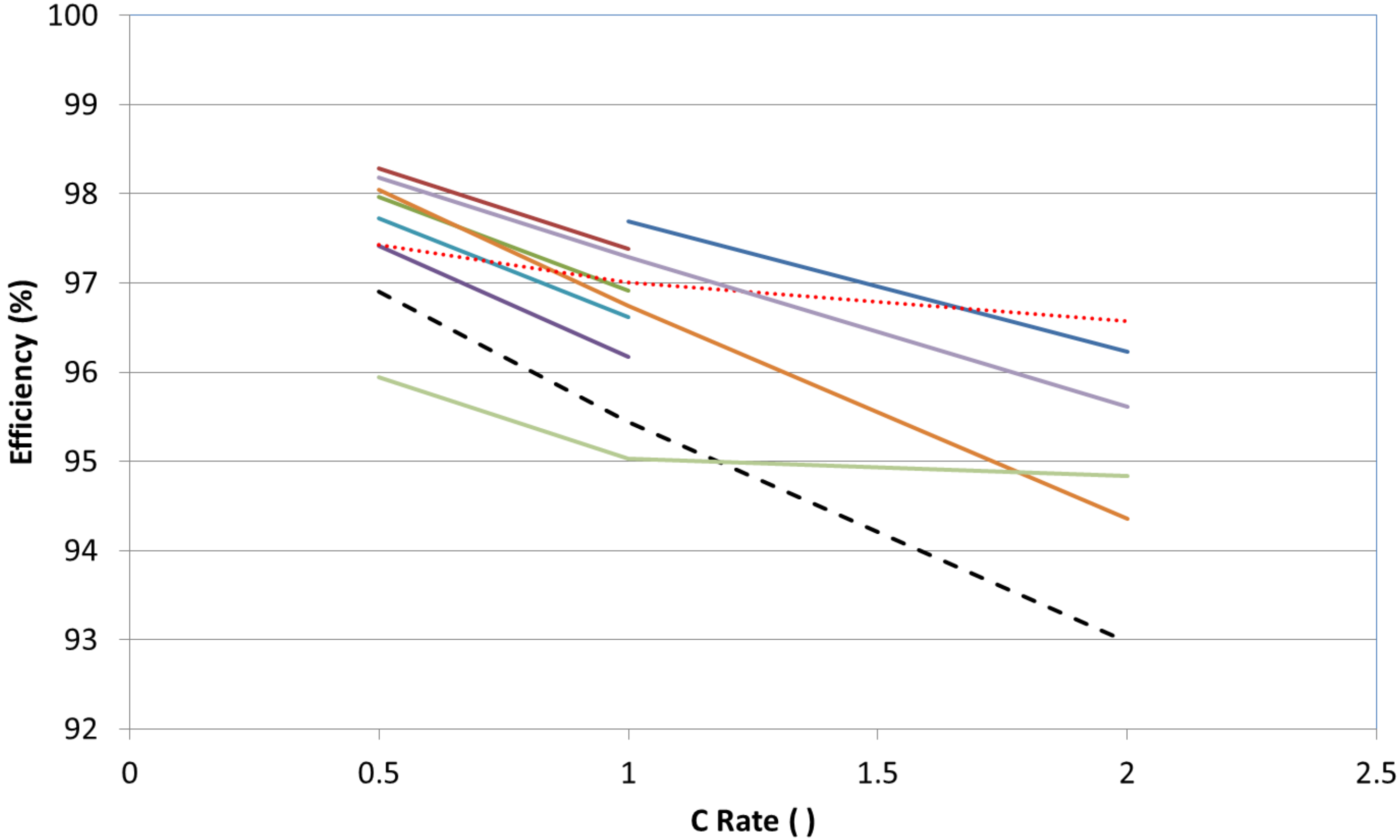


Photos by Matt Keyser, NREL



Efficiency Comparison of Cells Tested in FY13 and FY14 at 30ºC under Full Discharge from 100% to 0% SOC

Technical Lessons Learned



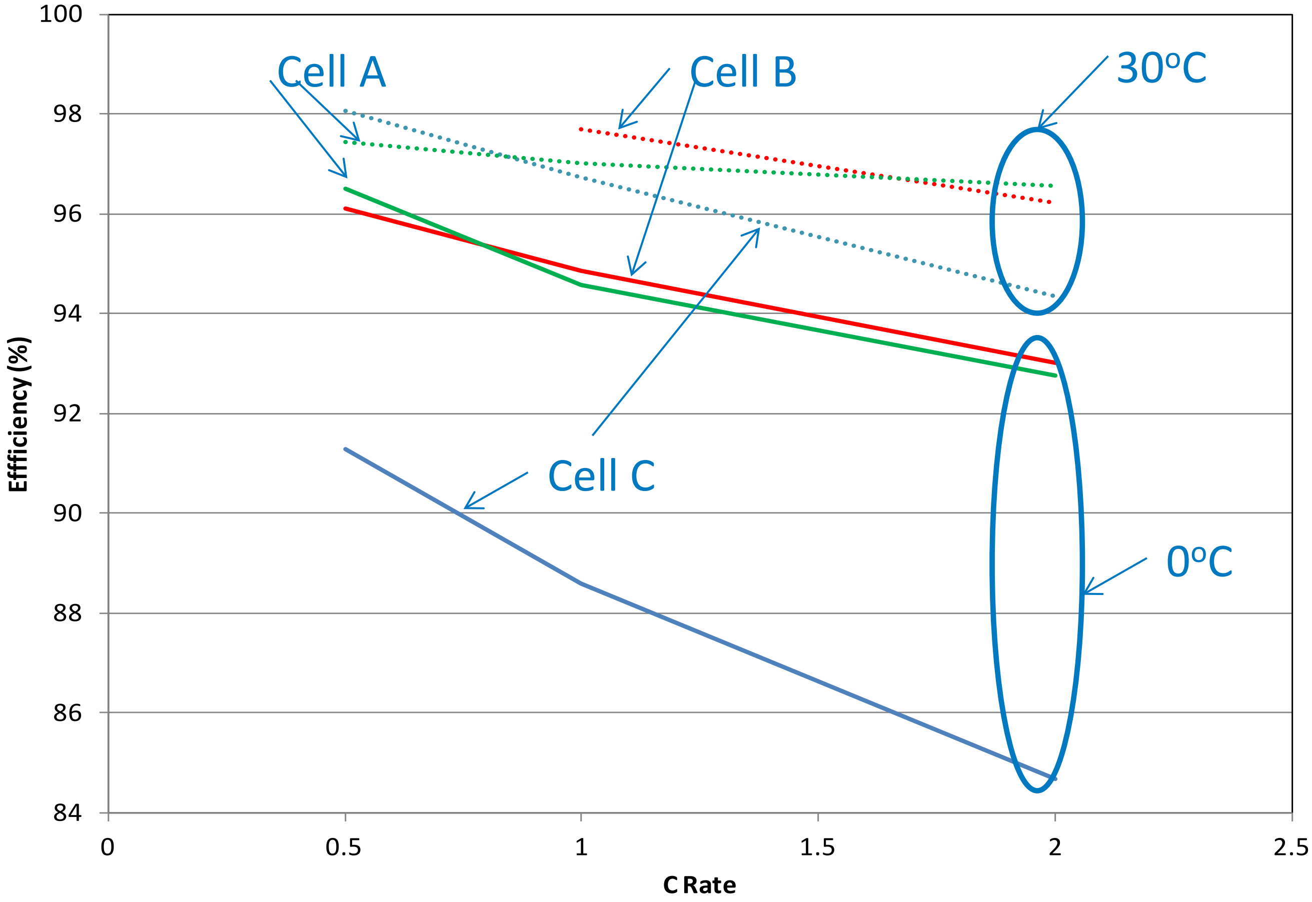
If the RMS PHEV/EV power profile is 20 kW, a 1% difference in efficiency will require the thermal management system to remove an additional 200 watts of thermal power – a substantial increase when considering most thermal systems are designed to remove only 300–600 watts.

RMS = root mean square

SOC = state of charge

Efficiency Comparison of Cells Tested in FY13/FY14 at 30°C and 0°C under Full Discharge from 100% to 0% SOC

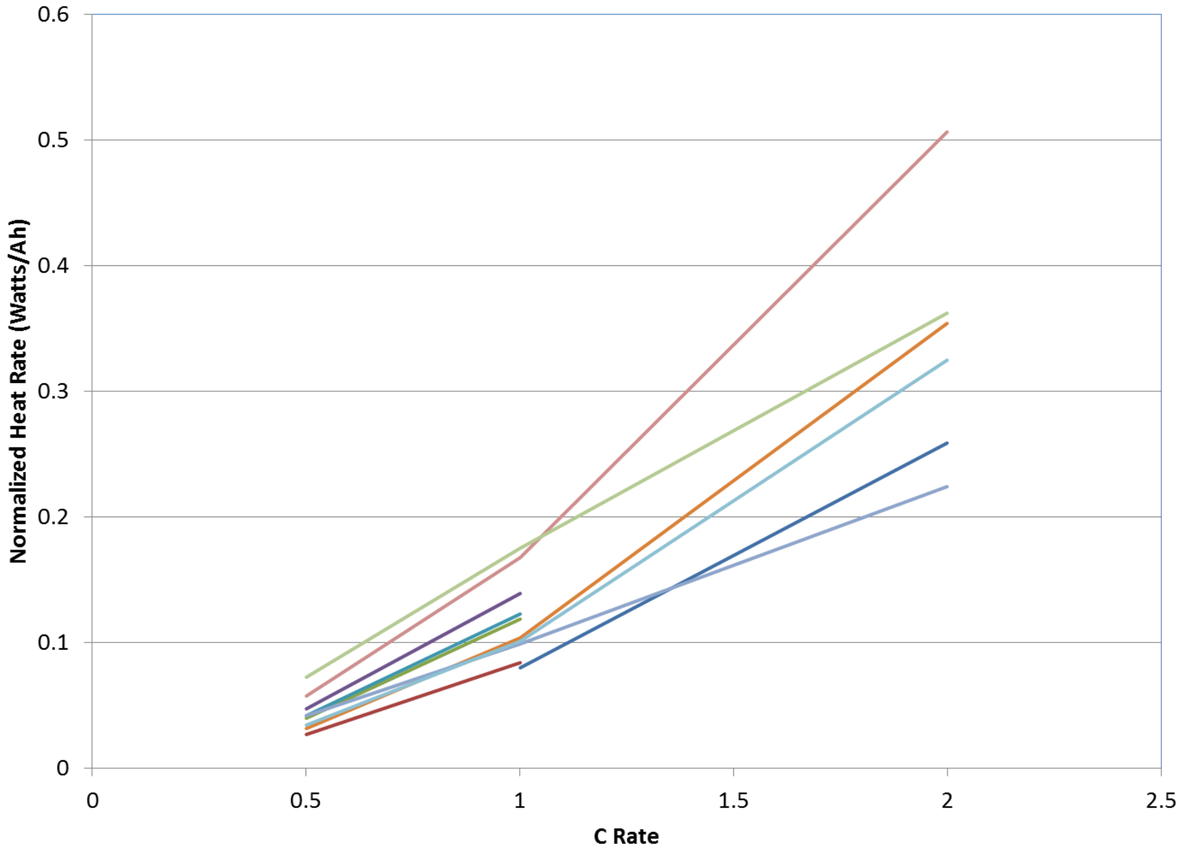
Technical Lessons Learned



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

Heat Generation Comparison of Cells Tested in FY13/FY14 at 30°C under Full Discharge from 100% to 0% SOC

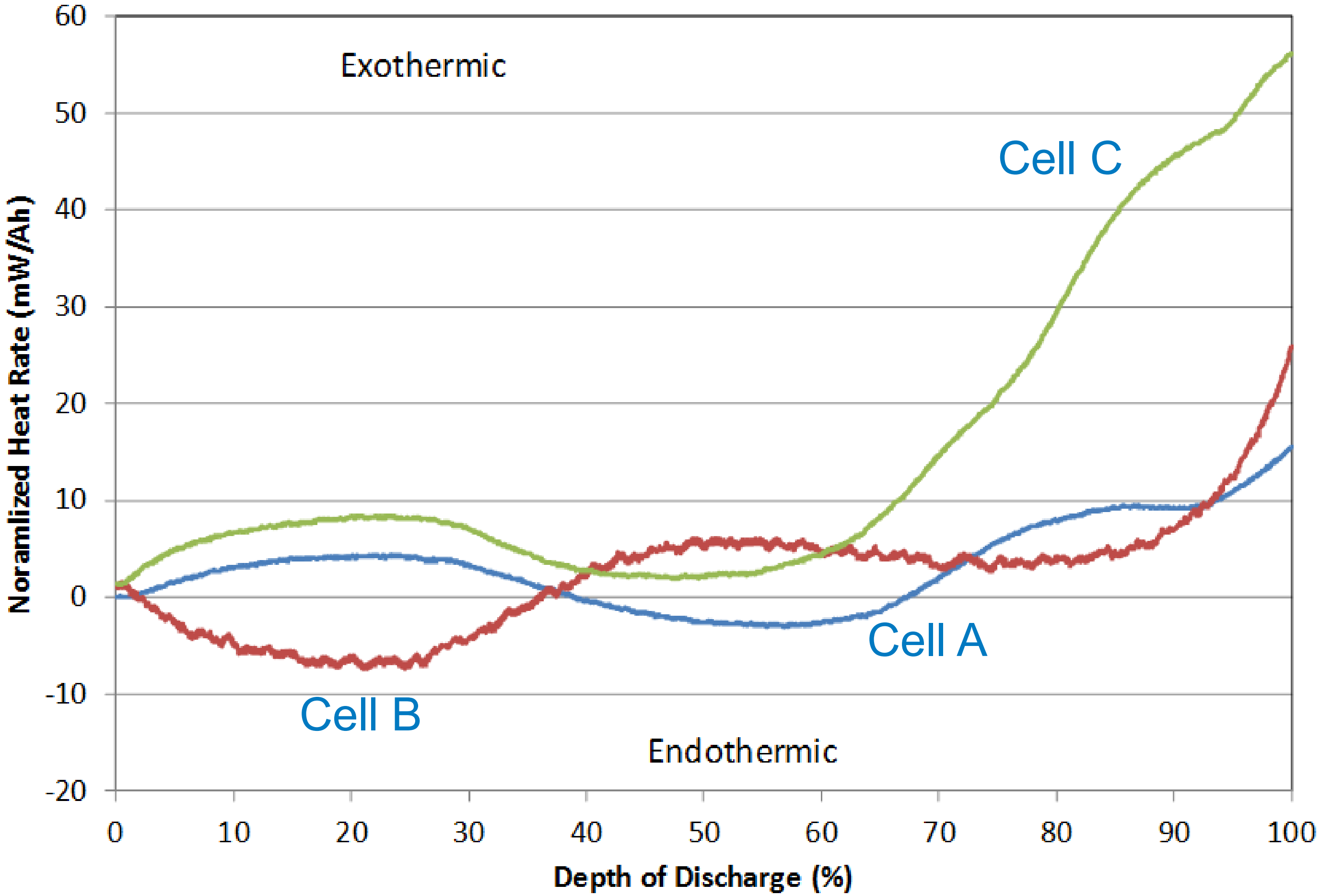
Technical Lessons Learned



Knowing how much heat is produced by the cell during different discharge/charge/drive cycles will allow for the proper design of the thermal management system, thereby decreasing the cycle life cost of the cell.

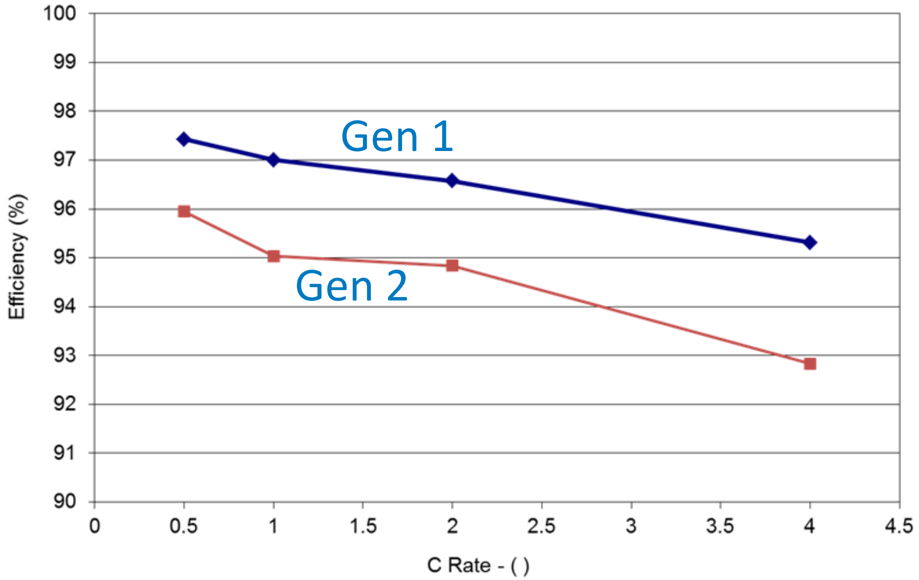
Entropic Cell Study
C/10 Constant Current Discharge at 30ºC

Technical Lessons Learned



Entropic studies identify regions of the discharge curve where cells are highly resistive – as an example, Cell C has a very high impedance below a depth of discharge of 80%.

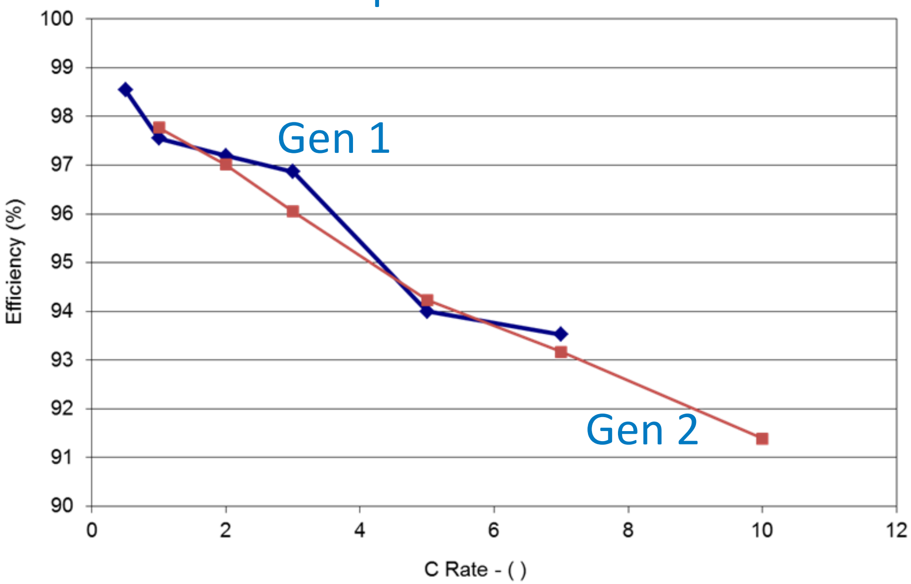
Efficiency Comparison of Successive Generations of Cells



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

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.

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

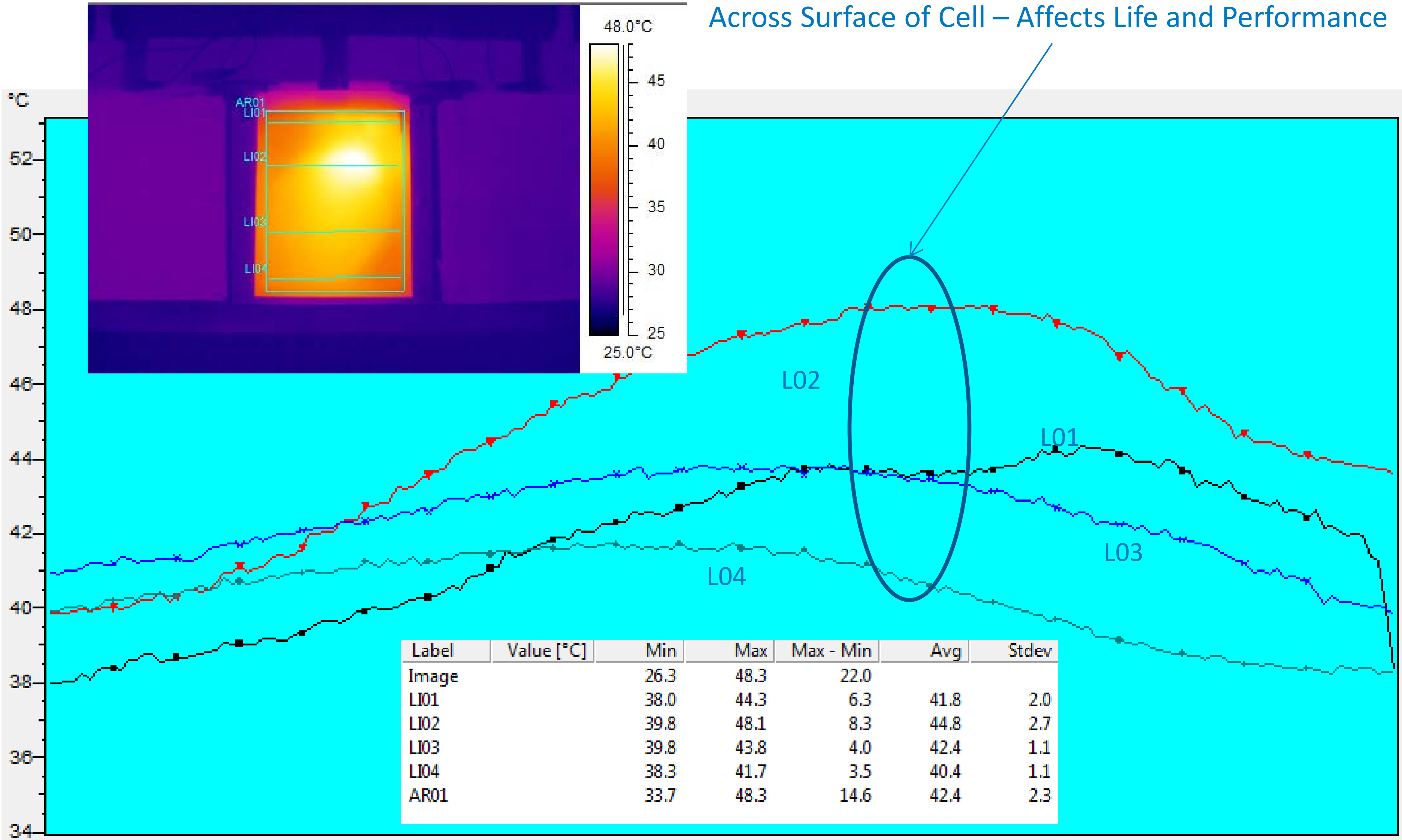


Technical Lessons Learned

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

Technical Lessons Learned

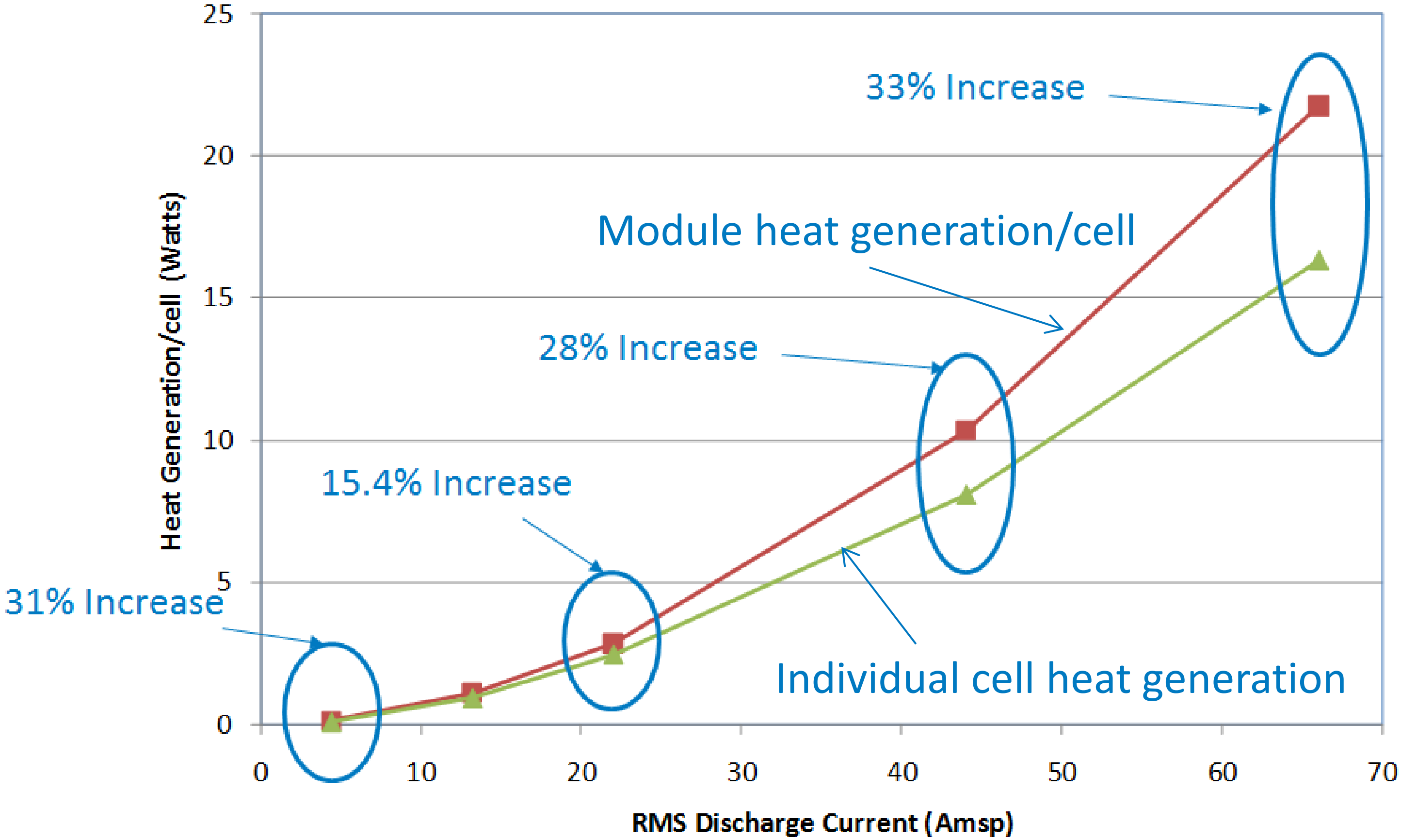
Large Temperature Variations
Across Surface of Cell – Affects Life and Performance



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

Cell versus Module Heat Generation

Technical Lessons Learned



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

Thermal Temperature Studies

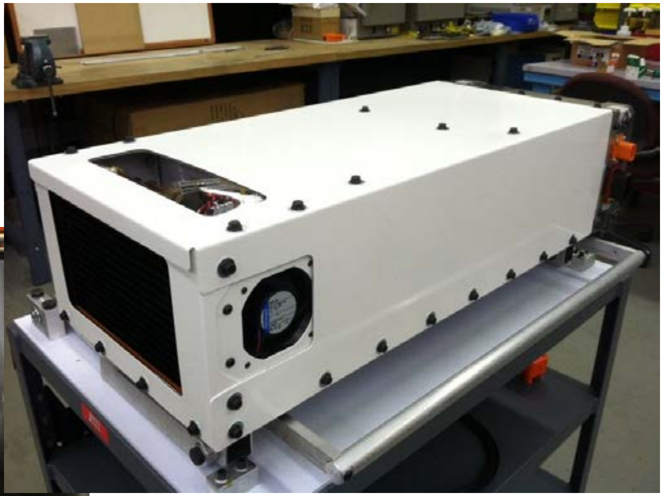
Technical Lessons Learned

Tested liquid (A123), air (JCS) and vapor compression (LGCPI) cooled packs.

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



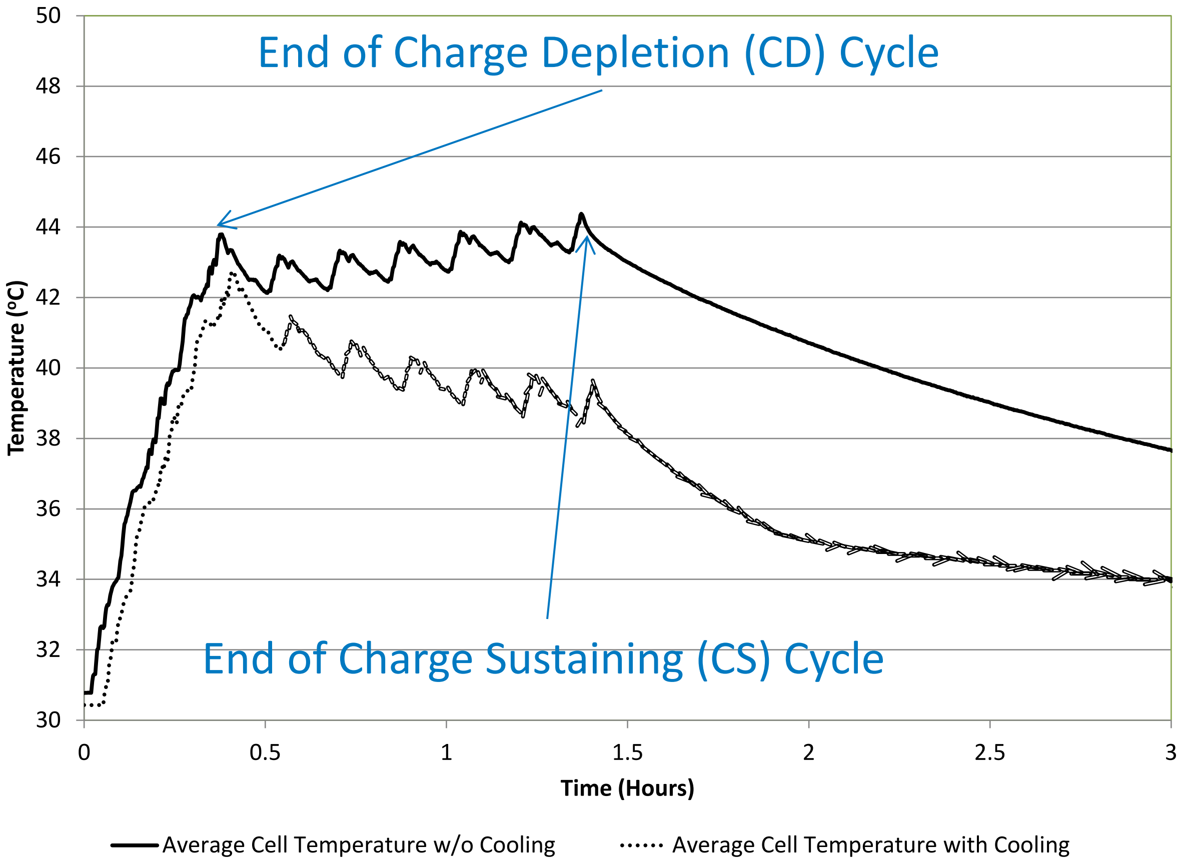
LGCPI

Thermal Management System Performance Under a PHEV Drive Cycle

Technical Lessons Learned

CD RMS Current = 63 Amps

CS RMS Current = 42 Amps



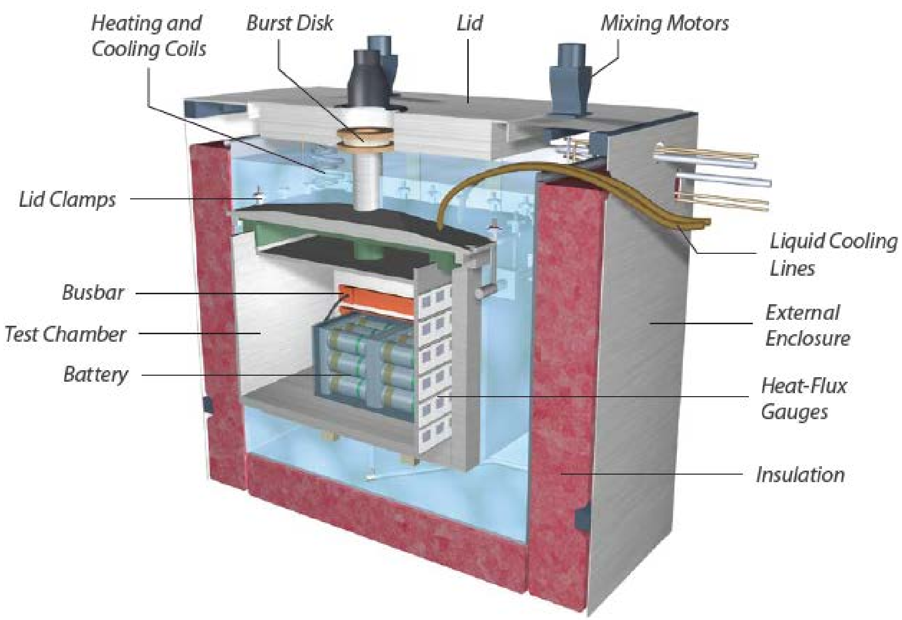
Some thermal management systems are not able to keep up with the heat being produced during high power cycles such as the CD portion above.

Responses to Previous Year Reviewers' Comments

Task was not presented at AMR in FY2013.

Collaboration with Industry: R&D100 Award-Winning Tools for Advancing Electric Drive Vehicles

The NREL large volume battery calorimeter (LVBC) design was licensed by Netzsch, a global manufacturer of scientific instruments. The Netzsch/NREL partnership led to the development of the IBC-284 isothermal battery calorimeter.



NREL LVBC Test Chamber

Netzsch IBC -284

Collaborators

- **USABC partners Chrysler, GM, and Ford**
- **USABC Contractors:**
    - ActaCell
    - Cobasys
    - Envia
    - Farasis
    - JCI
    - Leyden
    - LGCPI
    - Maxwell
    - Quallion
    - SK Innovation

Remaining Challenges and Barriers

- Address life issues at high and low temperatures - 15-year target.
- High energy storage cost due to battery packaging and integration costs.
- 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.

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.
- **Use thermal characterization data to enhance physics-based battery models in conjunction with DOE's Computer-Aided Engineering for Automotive Batteries (CAEBAT) program.**
- **Continue to develop 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.

Summary

- **Temperature** presents a significant challenge to vehicle energy storage life, safety, and performance, which ultimately impacts cost and consumer acceptance.
- **NREL laboratory tests** provide data to address thermal barriers of energy storage cells, modules, and packs. Results are reported to DOE, USABC, and industry partners.
- **Physics-based battery models** provide understanding of battery-internal behavior not possible through experiments alone. Data from NREL's experiments help to validate these models.