Thermal Implications for Extreme Fast Charge

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This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

- Project start date: 8/2016
- Project end date: 12/2016
- Percent complete: 100%

Budget

- Total project funding
  - DOE share: 100%
  - Contractor share: 0%
- Funding received in FY 2016: $225k
- Funding for FY 2017: $0k

Barriers

- Decreased battery life at high temperatures
- Cost, size, complexity, and energy consumption of thermal management system during extreme fast charging (XFC)
- Low energy efficiency of high specific energy density cells – advanced chemistries

Partners

- National Renewable Energy Laboratory (NREL)
  - Vehicle Pillar
- Argonne National Laboratory (ANL)
  - Battery Pillar
  - Economic Pillar
- Idaho National Laboratory (INL)
  - Infrastructure Pillar

Relevance of Battery Thermal Implications

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

Objectives of NREL's work

- Provide feedback to DOE on the battery thermal challenges associated with XFC
- Identify limitations of using high specific energy density cells
- Identify state-of-the-art thermal management strategies and how these can be applied to future battery electric vehicles (BEVs)
- Identify thermal areas of concern with present battery systems
- Identify how changes to the battery chemistry and cell design affect the cells' efficiency and performance
- Understand what areas need to be developed to make XFC a reality.

Milestones

Month / Year		Description of Milestone or Go/No-Go Decision	Status
12/2016	Milestone	Host stakeholder meeting at NREL to discuss direct current fast charge (DCFC)	Complete
12/2016	Milestone	Provide a written report to DOE describing vehicle technology gaps associated with DCFC	Complete
12/2016	Milestone	Provide a written report to DOE describing battery thermal management technology gaps associated with DCFC	Complete

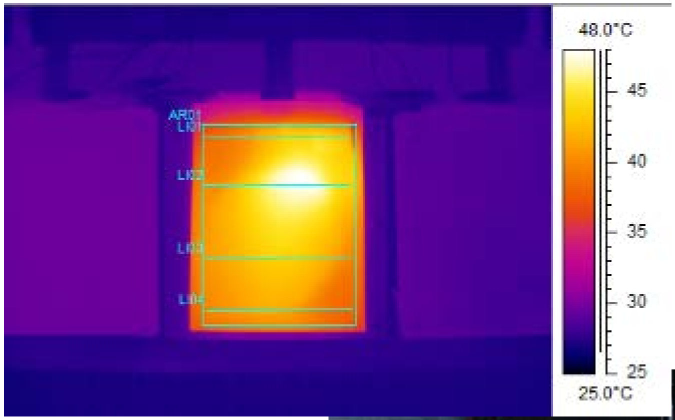
Approach – Stakeholder Meeting to Discuss DCFC

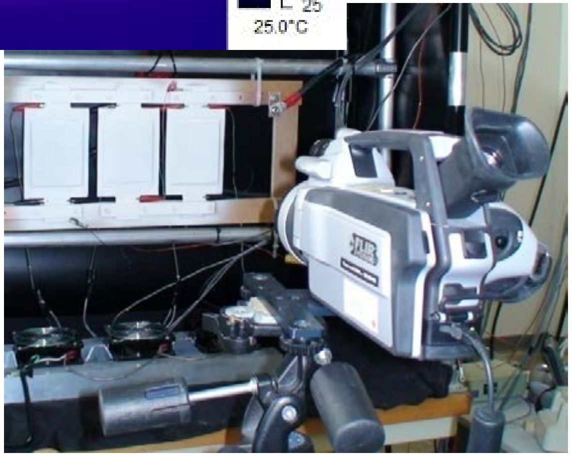
- NREL hosted two-day event to discuss the DOE's efforts to further develop electric vehicle (EV) DCFC
- Co-organized by ANL and INL
- Focused on the four pillars:
  - Battery, vehicle, infrastructure, and economic feasibility
- Meeting identified barriers and opportunities for the technology solutions needed to achieve EV charging at power levels up to 350 kW
- The meeting's objectives were to capture industry perspective on the future of charging to help guide the technology roadmap and best inform stakeholders on pursuing a faster metric for EV charging.

Approach – Thermal Testing

Thermal Imaging

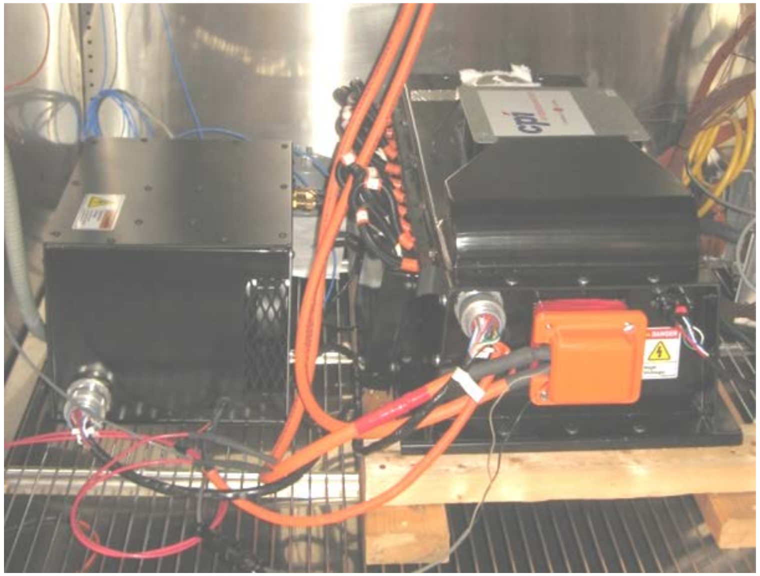
- **Temperature variation** across cell
- Profiles: US06 cycles, CC discharge/charge
- Unique non-destructive testing method to identify thermal areas of concern





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

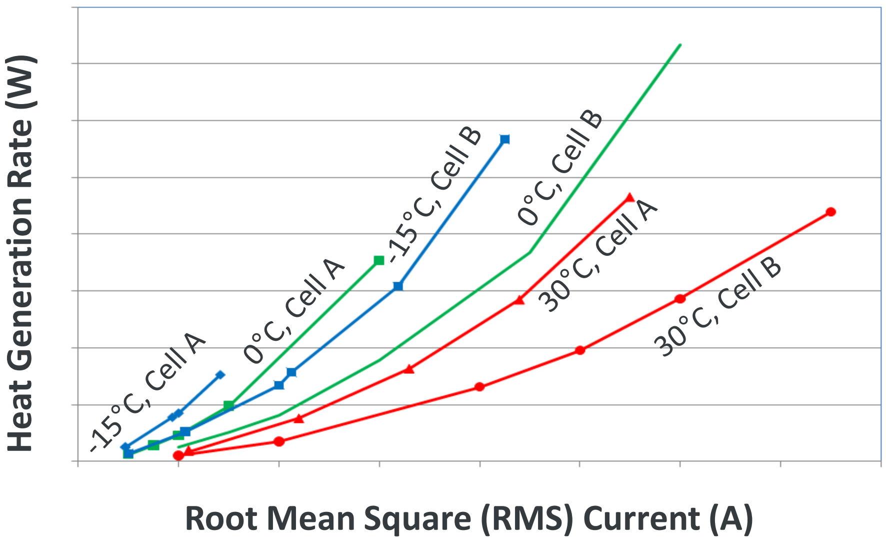
Results reported to DOE, USABC, and battery developers

Approach – Heat Generation and Efficiency

Using state-of-the-art isothermal battery calorimeters

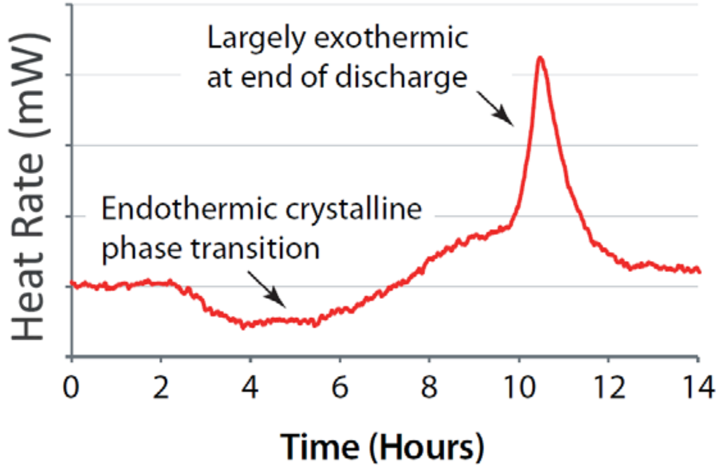
Top view of large calorimeter test chamber

Photo by Dennis Schroeder, NREL



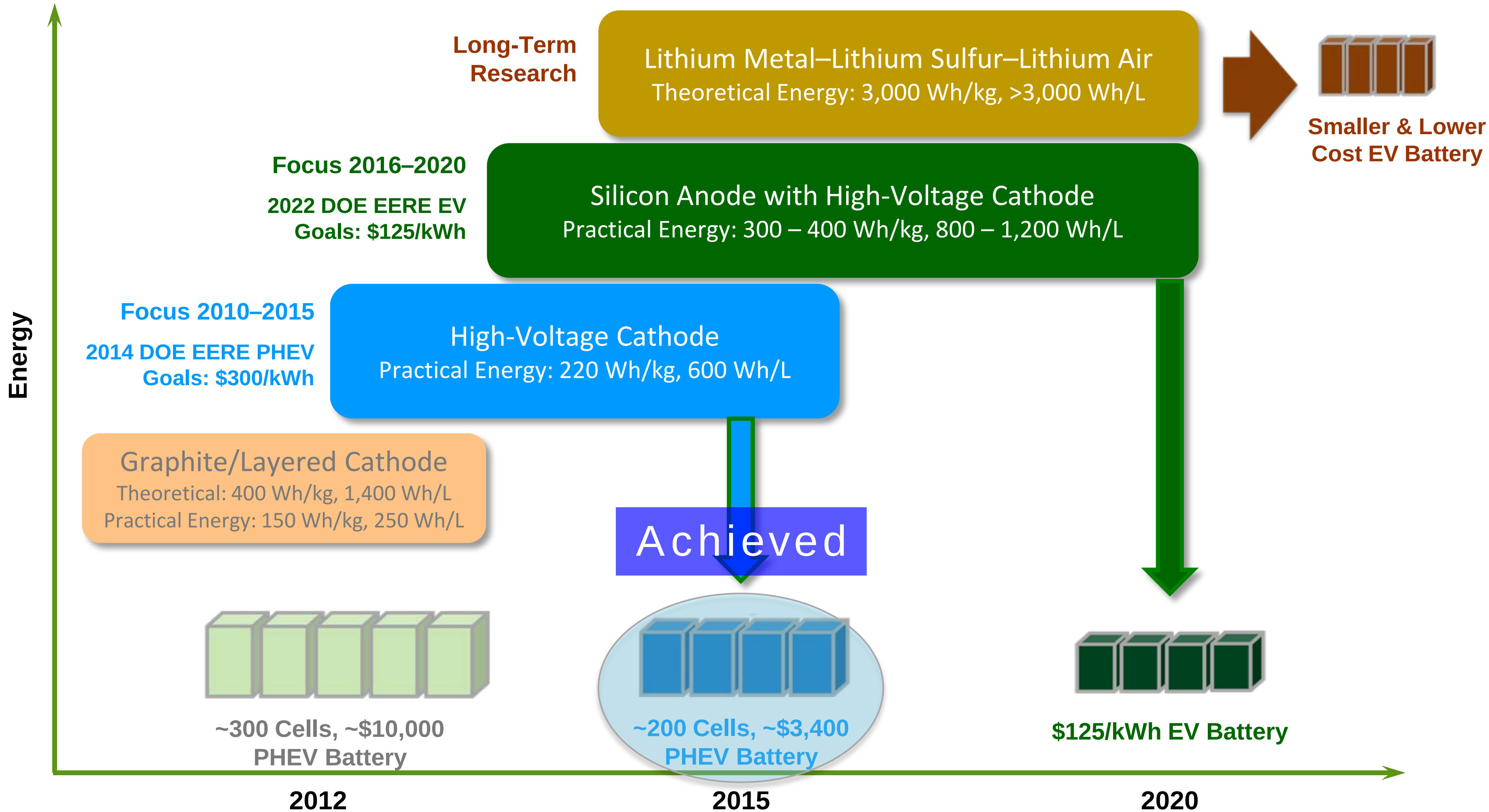
- **Heat generation**, heat capacity**,** and efficiency
- Test temperature range: -30°C to +45°C
- Profiles: USABC and US06 cycles, CC

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



Research Roadmap for 2015 & Beyond

Current emphasis: Development of high-voltage cathodes and electrolytes coupled with high-capacity metal alloy anodes. Research to enable lithium metal–lithium sulfur systems.



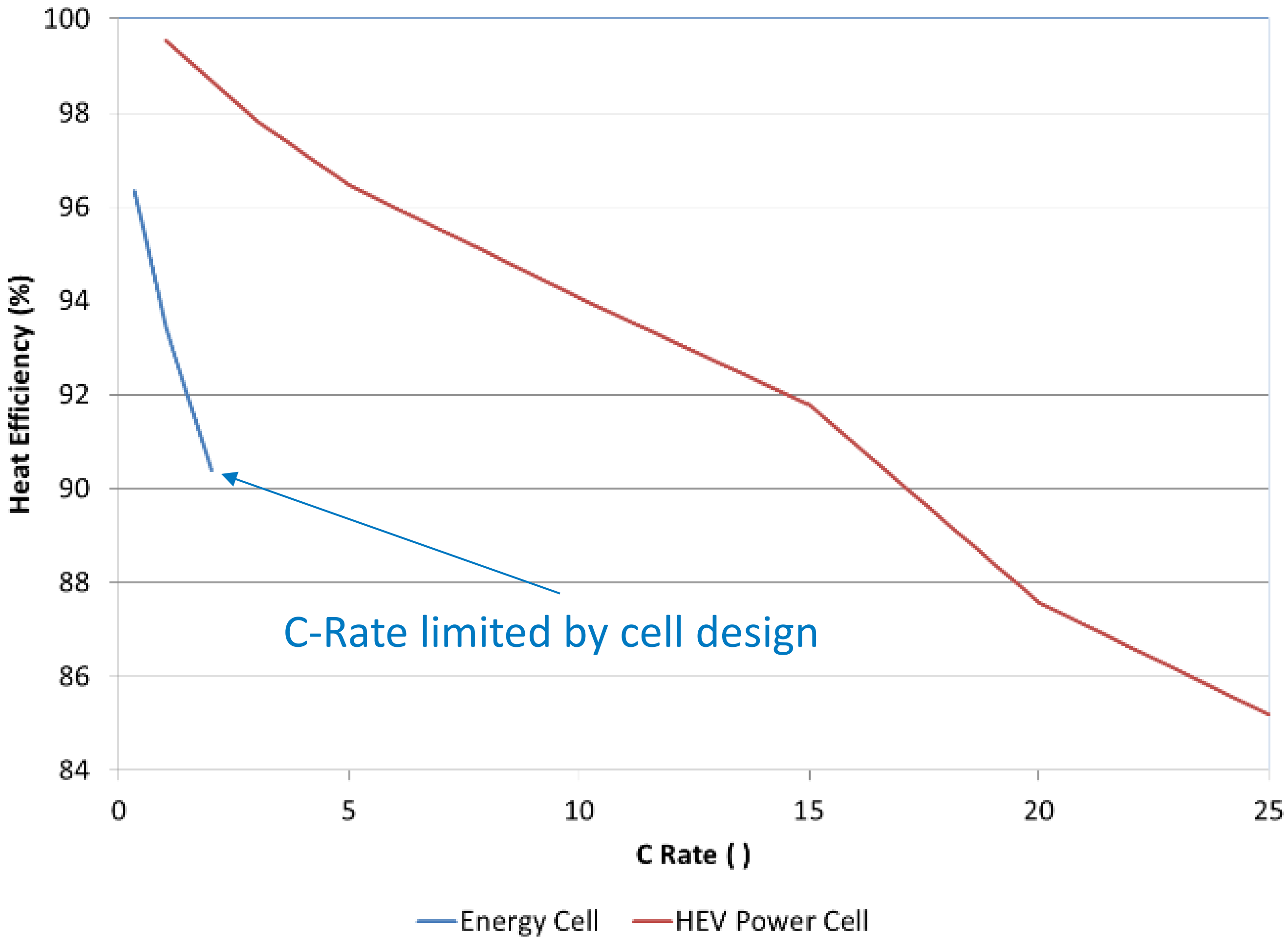
PHEV: plug-in hybrid electric vehicle

Courtesy: Dave Howell, DOE

Technical Accomplishments

- Lithium-ion batteries have very good coulombic efficiencies that are as high as 99.7%. The small drop in efficiency is often traced back to mismatched properties among the different battery components.
- The source of heat occurs in three areas:
  - Heat generation in the cell due to **Joule heating** is usually 50% of the heat budget of the cell.
  - Heat generation from **electrode reactions** contributes 30% – 40% of the heat losses.
  - **Entropic heat generation** contributes approximately 5% – 15% of the heat losses.

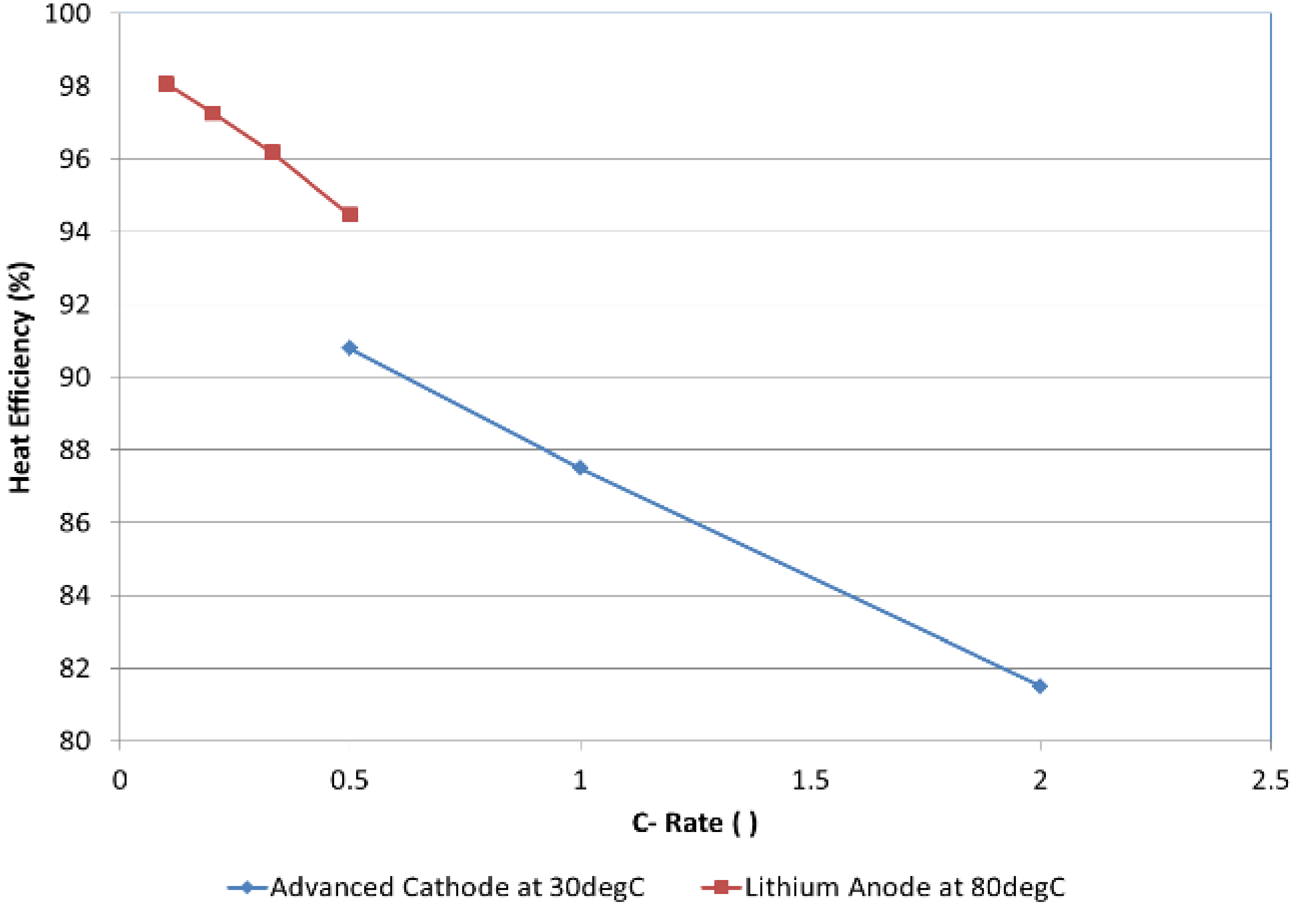
Technical Accomplishments



HEV: hybrid electric vehicle

Efficiency Limitations Associated with Advanced Chemistries

Technical Accomplishments



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

Temperature Study under XFC (1/2)

Technical Accomplishments

Performance Characteristics	Typical	Unit
Maximum Range Provided	200	Miles
Energy Used/Mile	0.33	KWh/mile
Pack Energy	66	kWh
Charger Power	350	KW

Case 1			Case 2		
Energy Density	175	Wh/kg	**Energy Density**	300	Wh/kg
Cell Number #	484	cells	**Cell Number #**	282	cells
Cell Efficiency	70	%	**Cell Efficiency**	90	%
Heat Removed	2	kW	**Heat Removed**	15	kW
Case 3			**Case 4**		
Energy Density	300	Wh/kg	**Energy Density**	175	Wh/kg
Cell Number #	282	cells	**Cell Number #**	484	cells
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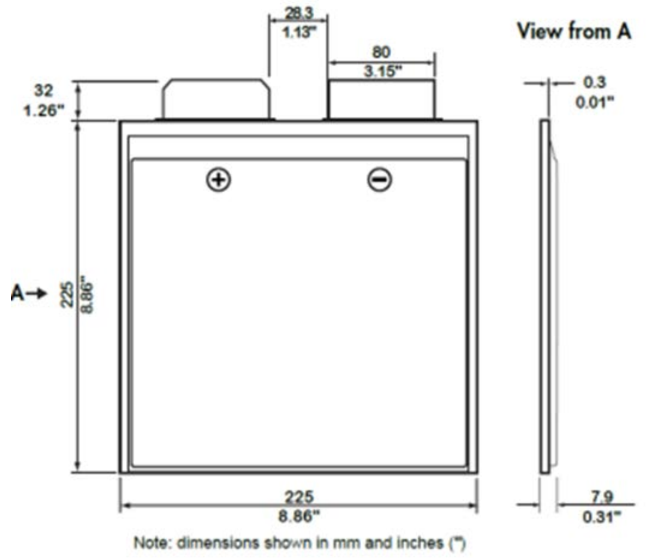

Temperature Study under XFC (2/2)

Technical Accomplishments

Case 1			Case 2		
Energy Density	175	Wh/kg	**Energy Density**	300	Wh/kg
Cell Efficiency	70	%	**Cell Efficiency**	90	%
Heat Removed	2	kW	**Heat Removed**	15	kW
Case 3			**Case 4**		
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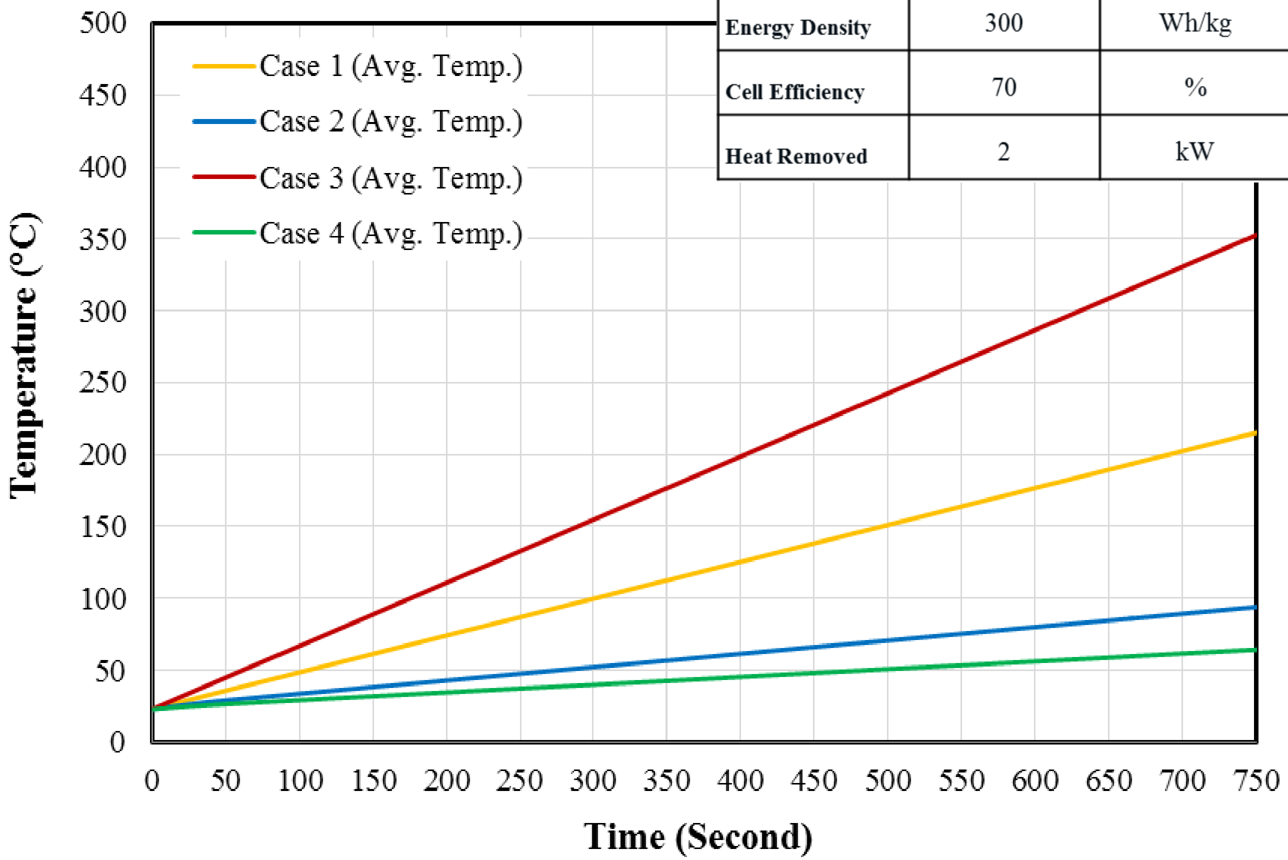
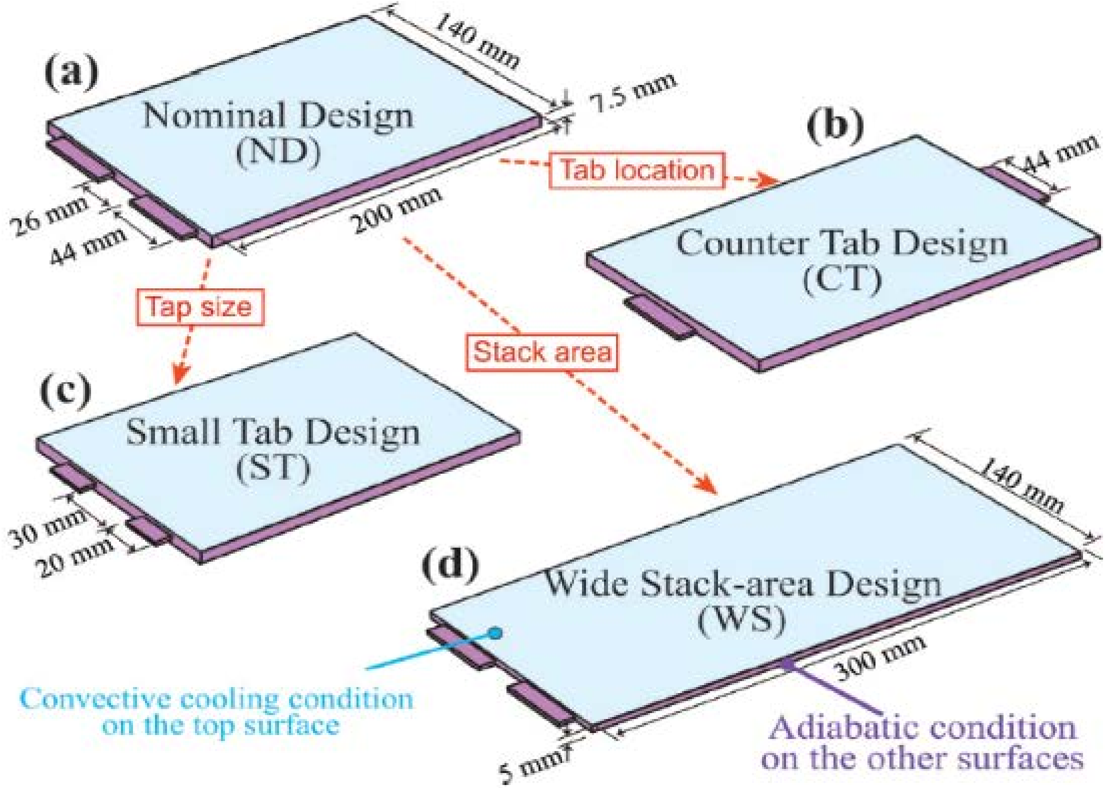


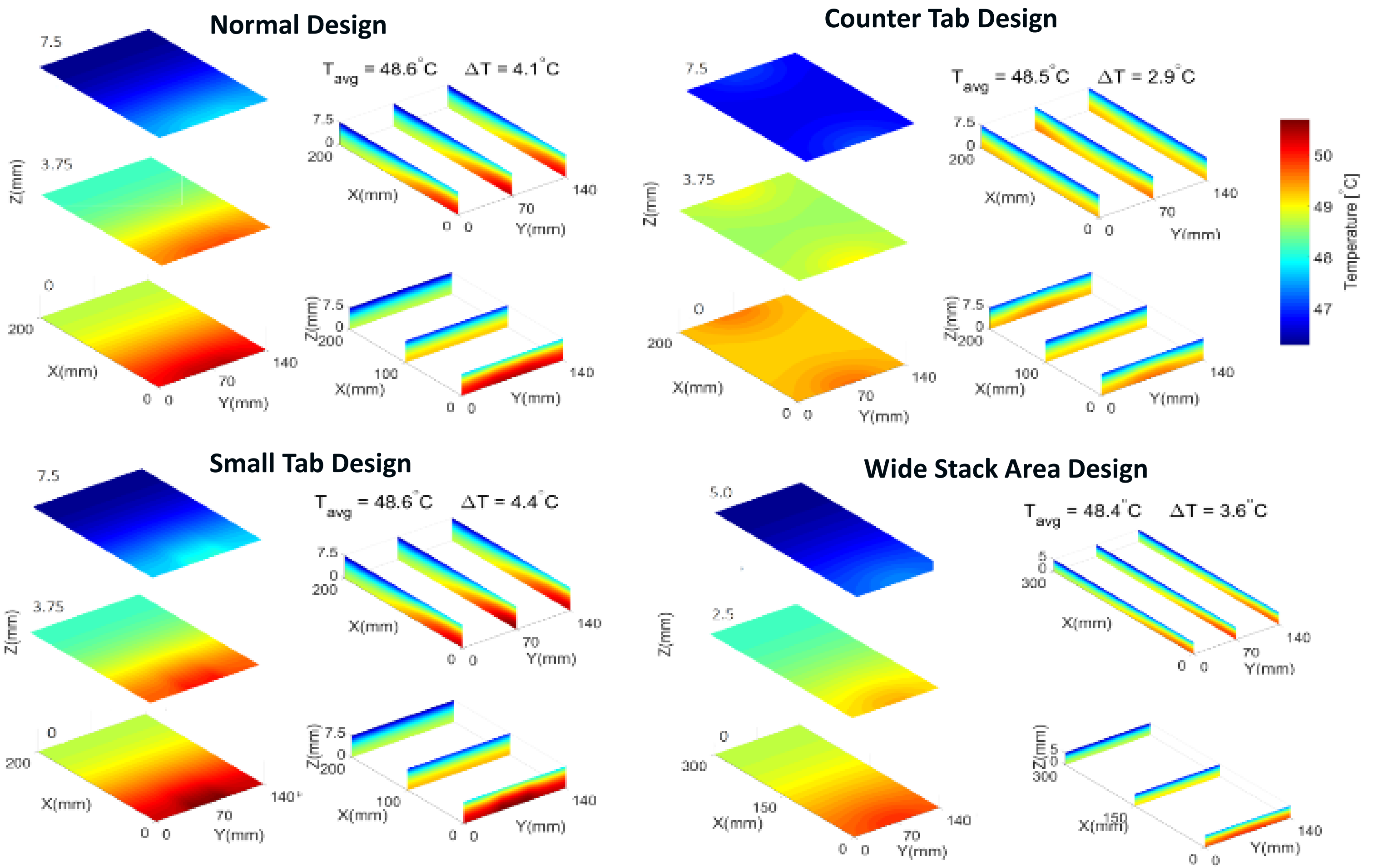
Cell Temperature Variation Exacerbated by XFC (1/2)

Technical Accomplishments



Study performed for a 5C fast charge with an average heat efficiency of 90%.

Technical Accomplishments

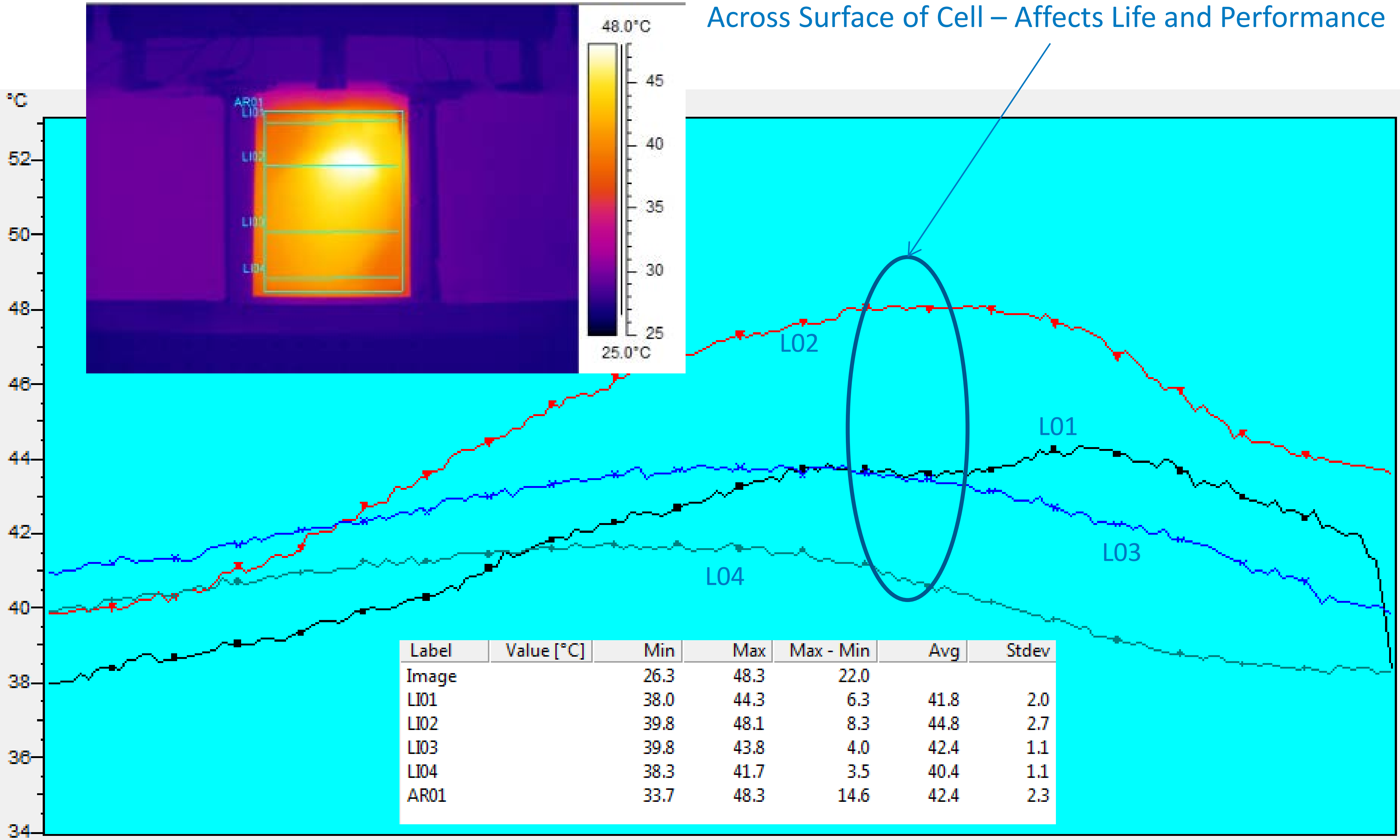


USABC Cell Temperature Variation Goal < 3°C

USABC: United States Advanced Battery Consortium

Technical Accomplishments

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 Design Thermal Considerations

- Increasing the amount of carbon black or other conductive material in the cathode and anode.
- Increasing the thickness of the current collectors
- Incorporate low-temperature phase change material within the cell to absorb heat where it is generated. Is it feasible to modify the cell with an electrochemically inert material?
- Continuous current collectors have a more optimal heat conductive path. Do we eliminate stacked cells from consideration? Cylindrical cells have a low packing density; do we look at oval cells in a prismatic package? Is there an optimal battery form factor for thermal design?

USABC Thermal Goals for Electrified Vehicles

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	

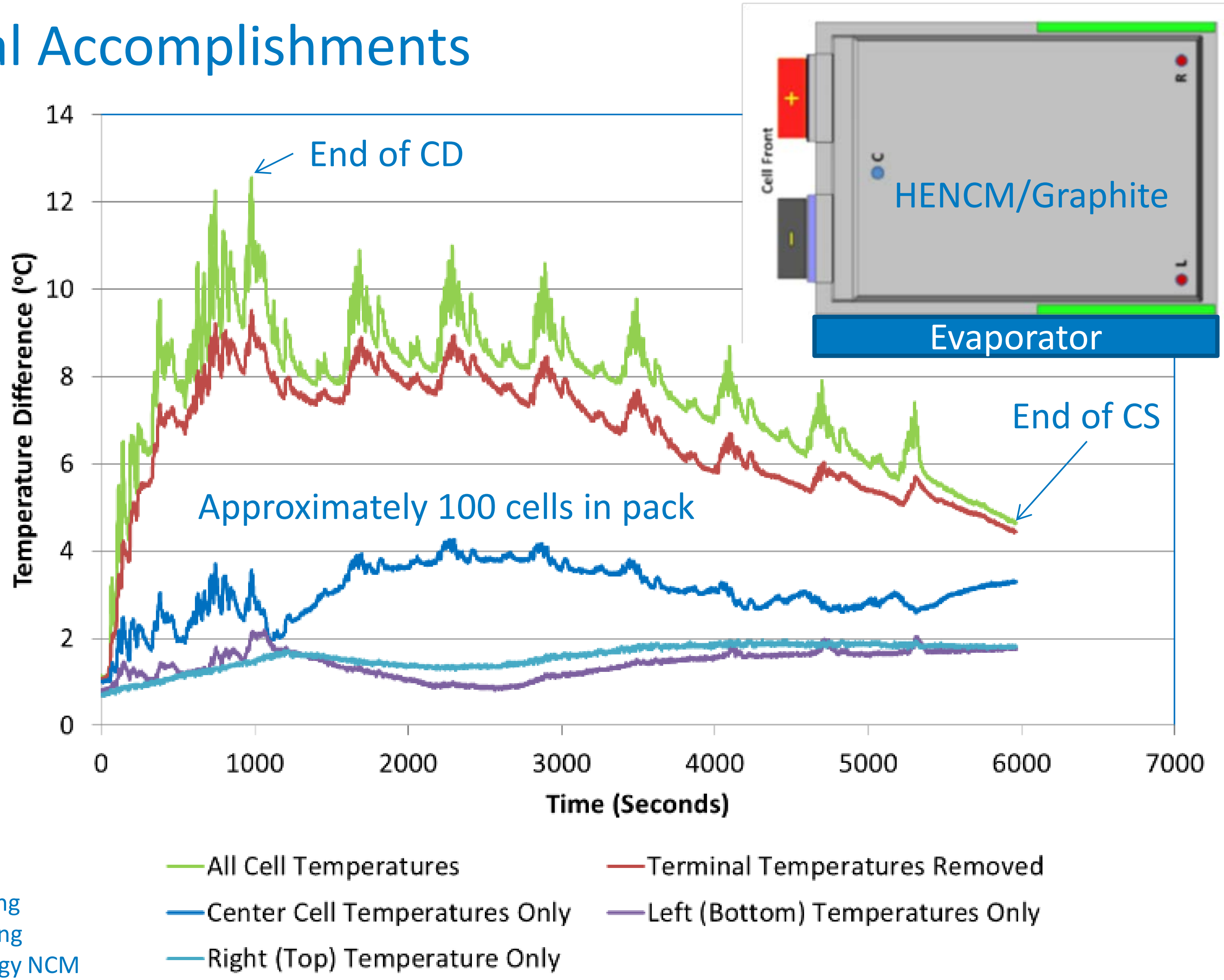
Evaluating new thermal management systems according to USABC guidelines.

Thermal Management Strategies

Strategy	Air Cooling	Liquid Cooling	Active Cooling
Temperature Uniformity	+	+	+
Heat Transport	-	+	+
Thermal Control	-	+	+
Electrical Isolation	+	-	+
Compact Design	+	-	-
Maintenance	+	-	-
Cost	+	-	-
Weight	+	-	-
Ancillary Power	+	+	-
Noise	-	+	-

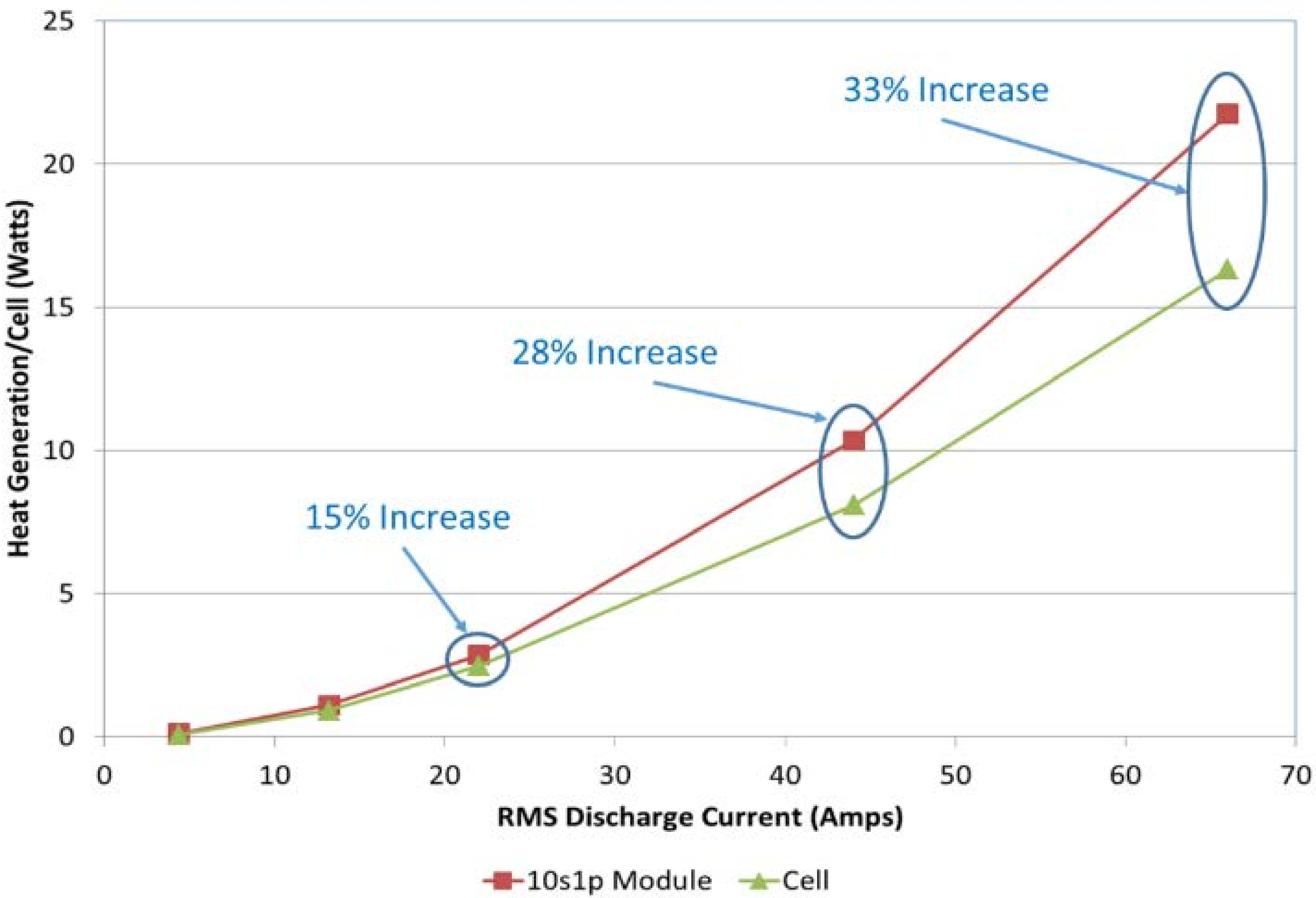
Present BEV cooling systems range from 1-5 kW. This may need to be increased substantially to meet XFC demands. In addition, new cooling strategies may need to be considered such as jet impingement, immersion, etc…

Technical Accomplishments



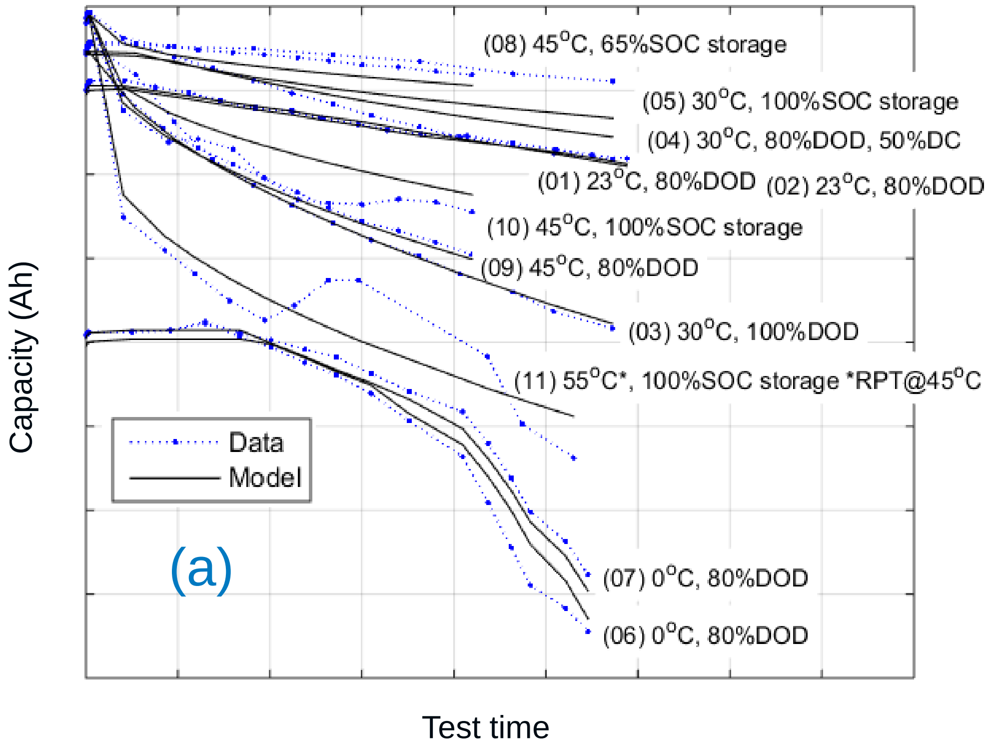
CD = charge depleting
CS = charge sustaining
HENCM = High Energy NCM

Pack Design Will Be Important to Ensure Thermal Uniformity

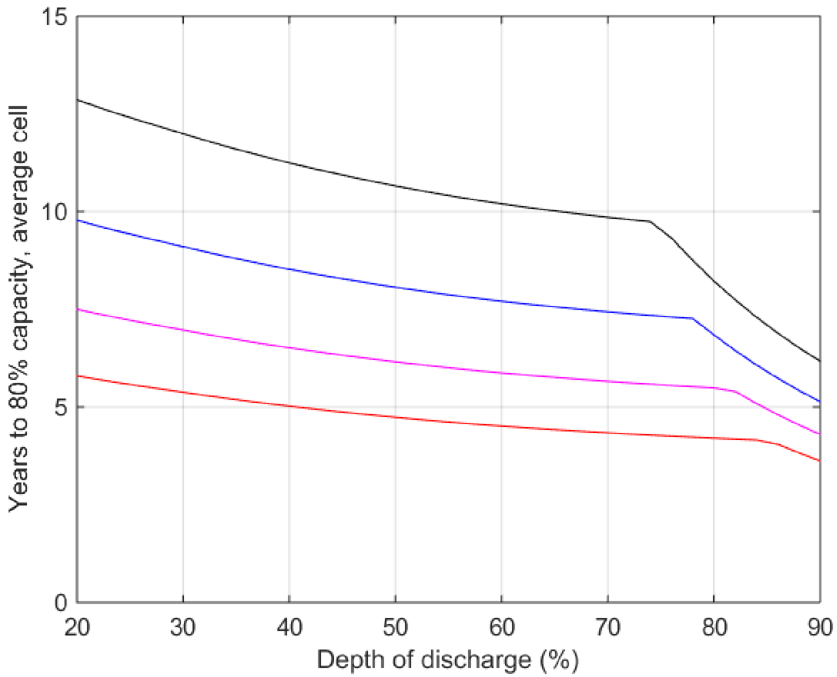


Under XFC the battery interconnect design will have added importance.

Temperature has an Effect on Life



How life is affected will depend on how often the driver utilizes fast charging stations.



DOD = depth of discharge
SOC = state of charge

Response to Previous Year Reviewers' Comments

- Not reviewed at the 2016 AMR.

Collaborations

- National Labs
  - [1]Argonne National Laboratory (ANL)
  - [2]Idaho National Laboratory (INL)
  - [3]National Renewable Energy Laboratory (NREL)
- Received input from stakeholders
  - Vehicle original equipment manufacturers (OEMs)
  - Battery manufacturers
  - Utilities
- Team
  - Shabbir Ahmed,[1] Ira Bloom,[1] Andrew Burnham,[1] Barney Carlson,[2] Fernando Dias,[2] Eric J. Dufek,[2] Keith Hardy,[1] Andrew N. Jansen,[1] Matthew Keyser,[3] Cory Kreuzer,[3] Anthony Markel,[3] Andrew Meintz,[3] Christopher Michelbacher,[2] Manish Mohanpurkar,[2] Paul A. Nelson,[1] Ahmad Pesaran,[3] David C. Robertson,[1] Don Scoffield,[2] Matthew Shirk,[2] Thomas Stephens,[1] Tanvir Tanim,[2] Ram Vijayagopal,[1] and Jiucai Zhang[3]

Summary

- Robust battery thermal management will be required to make XFC a reality – even with high-power cells, an oversized battery thermal management system will needed.
- The size of the battery thermal management system will have to increase from today's BEV average size of 1–5 kW to around 15–25 kW.
- The heat efficiency of high energy density cells will need to improve by 10%–20% at high rates of charge.
- New thermal management strategies like jet impingement or immersion of the battery in a dielectric fluid may need to be investigated to keep the battery below the operational maximum temperature limit.
- The cell-to-cell imbalance due to EFC will affect the longevity and cycle life cost of the cells. New passive and/or active battery management systems will need to be investigated to ensure that the batteries meet the OEM's warranty obligations.
- Cell design will have an impact on the temperature variation within the cell and the temperature imbalance within the pack.
- The mean average temperature of the battery directly affects the cycle life of the battery. High EFC utilization by the driver will have a strong influence on this metric.
- Additional cooling at the EFC station may be required to ensure a complete charge of the battery pack.