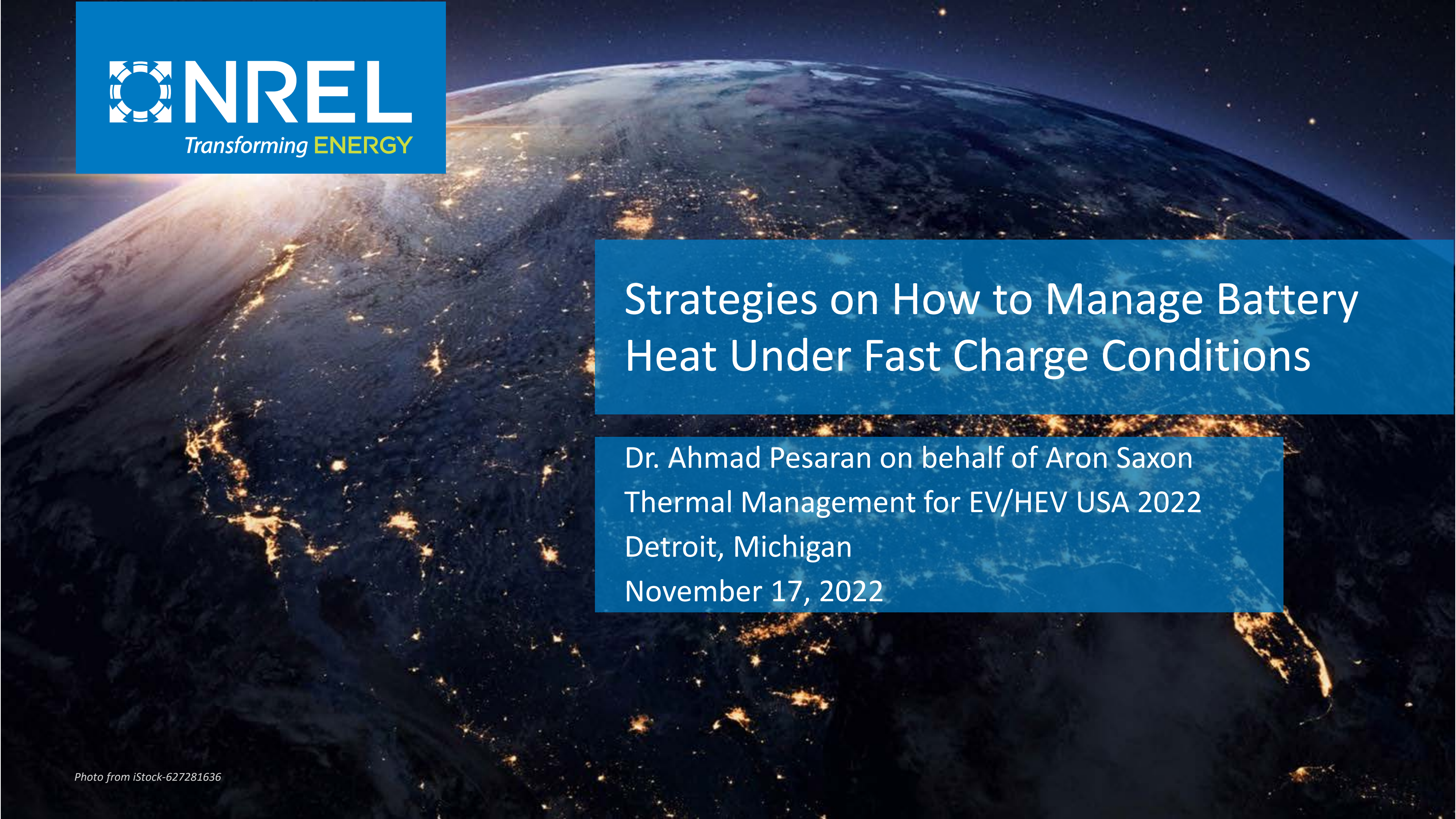


Strategies on How to Manage Battery Heat Under Fast Charge Conditions

Dr. Ahmad Pesaran on behalf of Aron Saxon
Thermal Management for EV/HEV USA 2022
Detroit, Michigan
November 17, 2022

Photo from iStock-627281636

NREL at-a-Glance

2,926

Workforce, including

219 postdoctoral researchers

60 graduate students

81 undergraduate students

World-class

facilities, renowned technology experts

More than **900**

Partnerships

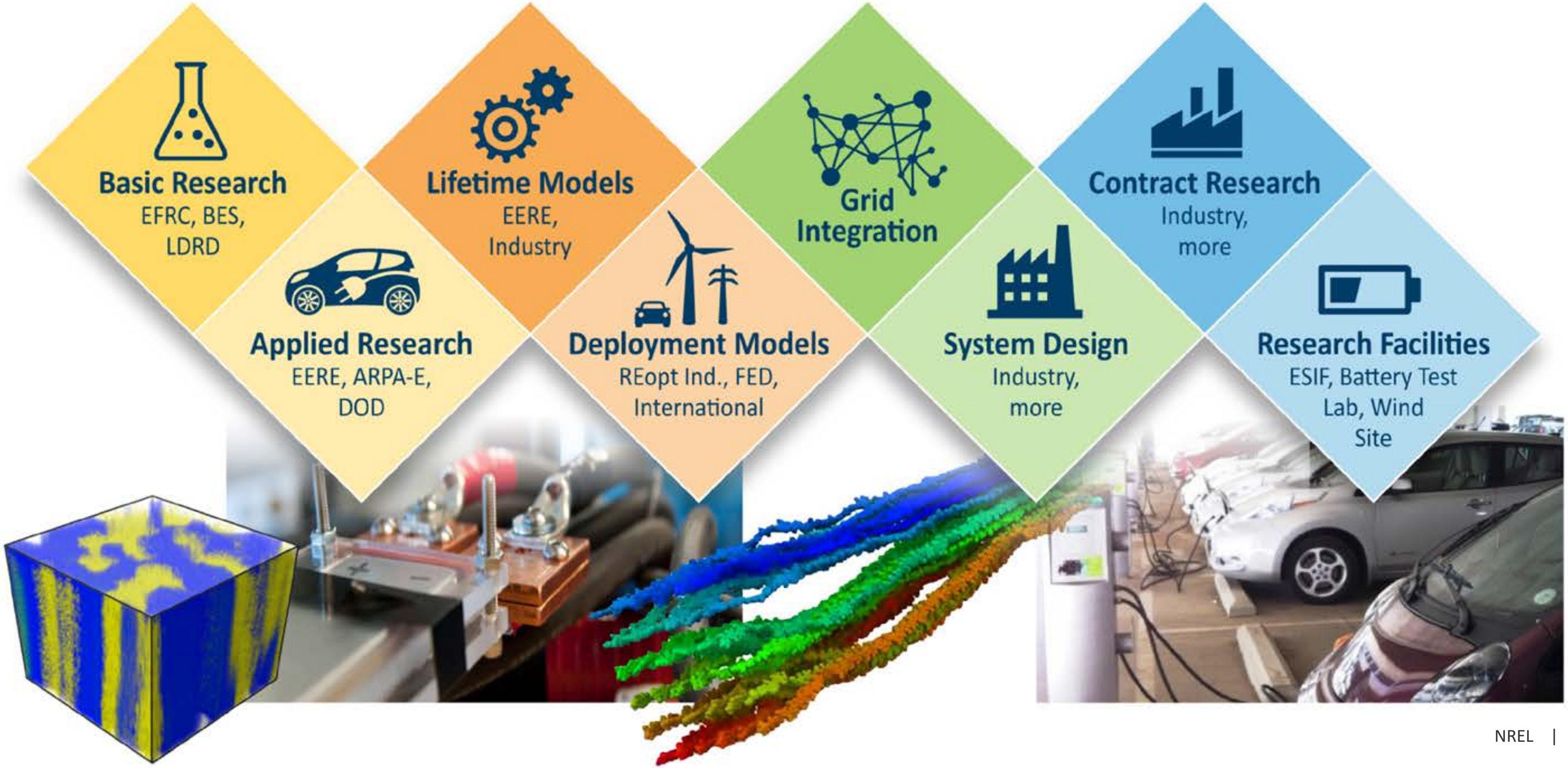
with industry, academia, and government

Campus

operates as a living laboratory

Photo by Joshua Bauer / NREL

NREL’s Range of Energy Storage R&D



Basic Research
EFRC, BES,
LDRD

Applied Research
EERE, ARPA-E,
DOD

Lifetime Models
EERE,
Industry

Deployment Models
REopt Ind., FED,
International

Grid Integration

System Design
Industry,
more

Contract Research
Industry,
more

Research Facilities
ESIF, Battery Test
Lab, Wind
Site

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1. Introduction and Overview
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Why Extreme Fast Charge (XFC)

XFC allows full market penetration of battery electric vehicles (BEV) while solving the current equity issue of BEVs only being feasible to people that can charge at home.

Photo by Dennis Schroeder, NREL

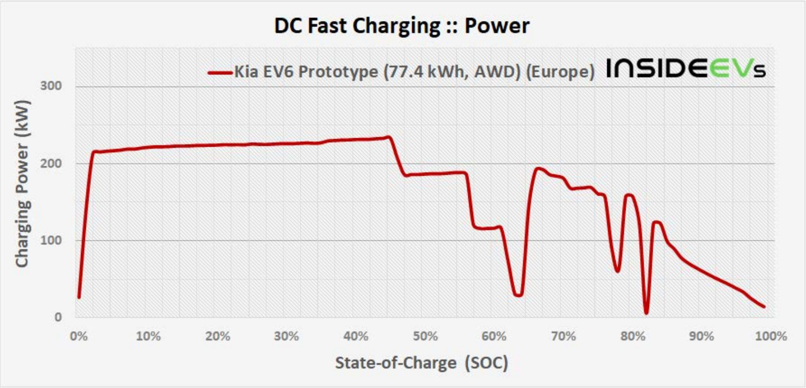
XFC Today

Current state-of-the-art charging enables high power at low SoC but suffers from lower power levels at high SoC.

Current BEV DC Fast Charge Capabilities

Car Make and Model	Battery Capacity	Maximum Power	Charge Time (10%-80% SoC)	Average Power
Kia EV6 Long Range 2WD	77.4 kWh	233 kW	16 min	200 kW
Hyundai IONIQ 5 Long Range 2WD	77.4 kWh	233 kW	16 min	200 kW
Porsche Taycan 4S Plus	93.4 kWh	268 kW	17 min	216 kW
Audi e-tron GT Quattro	93.4 kWh	268 kW	17 min	216 kW
Lucid Air Pure	88.0 kWh	200 kW	24 min	160 kW
Tesla Model 3 Long Range AWD	82.0 kWh	250 kW	27 min	124 kW

Source: ev-database.org

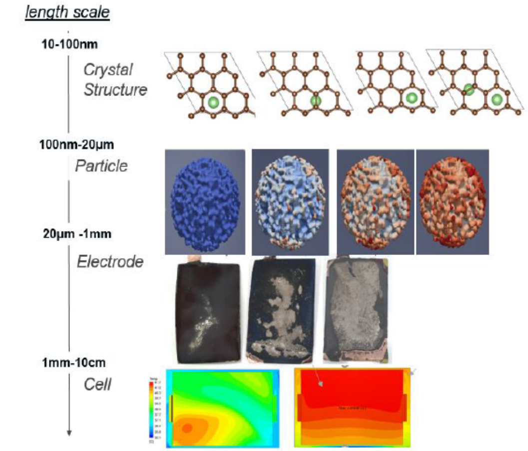


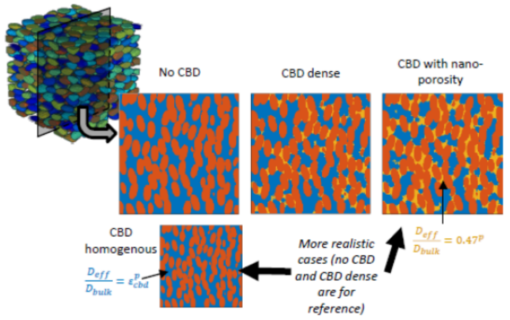
Source: insideevs.com/news/537223/kia-ev6-prototype-fast-charging/

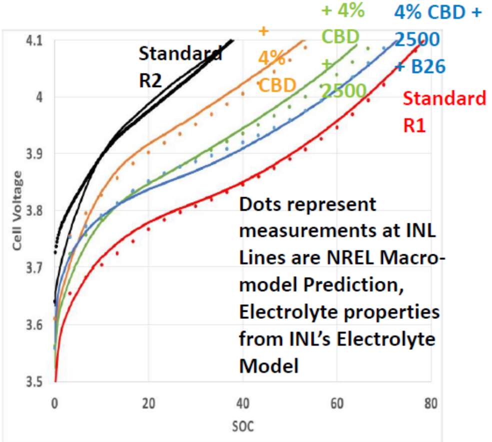
XFC Tomorrow: DOE XCEL Program

Enable fast charging (10 minutes or less) of high-capacity batteries (above 200Wh/kg) while minimizing life impacts.

- Developing a fundamental understanding of the complex multivariable interactions at different length scales
- Exploring novel electrode designs with state-of-the-art materials
- Charge rate optimization







Dots represent measurements at INL
Lines are NREL Macro-model Prediction,
Electrolyte properties from INL's Electrolyte Model

Taken From: Howell, Dave. 2021. "Vehicle Technologies Office Battery R&D Overview." Presented at ARPA-E High Energy, Fast Charging Batteries for EV Applications Workshop.

Objectives of NREL’s Battery Thermal Management Work

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

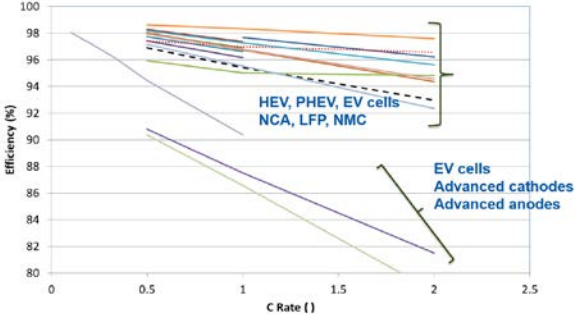
- To thermally characterize cell and battery hardware and provide technical assistance and modeling support to DOE/U.S. DRIVE, USABC, and battery developers for improved designs
- Identify how changes to the battery chemistry and cell design affect the cells’ efficiency and performance
- To quantify 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.

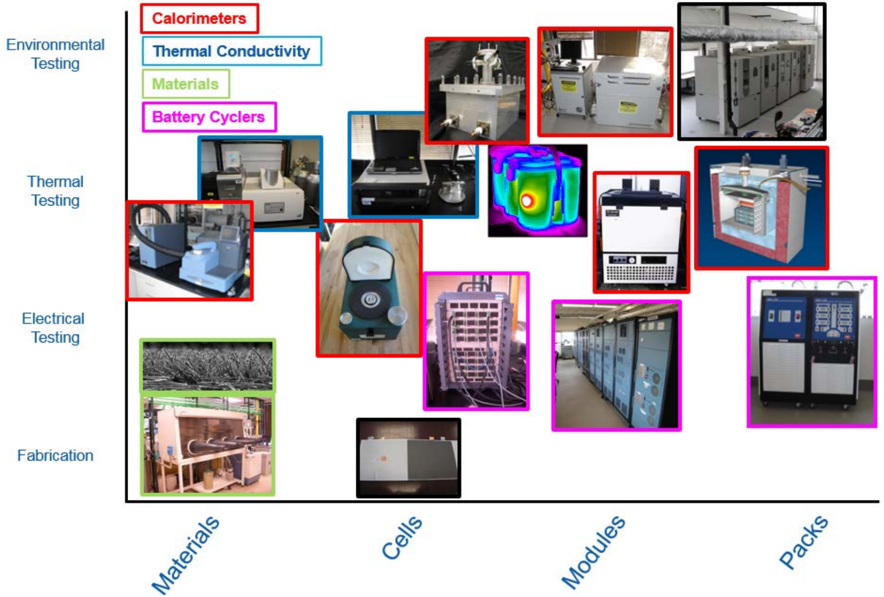
USABC = U.S. Advanced Battery Consortium

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

Thermal Characterization & Analysis

- As part of the United States Advanced Battery Consortium’s (USABC) Technical Advisory Committee, we benchmark different cells/chemistries
- This activity also helps advise multiple standards committees, roadmaps, etc.



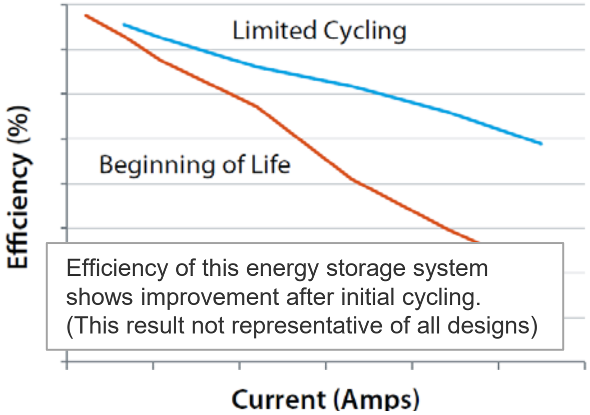


Pack, Module, and Cell Calorimeters

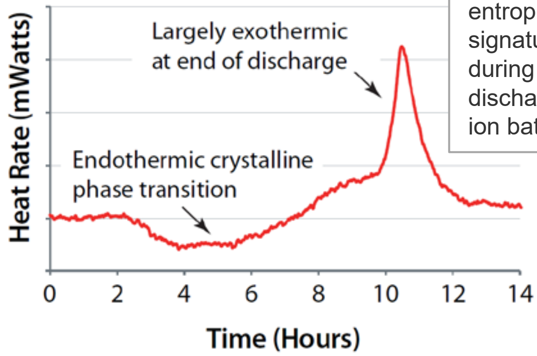
Cell, Module, & Pack Level Testing

Top view of large calorimeter test chamber

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 of this energy storage system shows improvement after initial cycling. (This result not representative of all designs)



Phase transitions visible in the entropic signature during slow discharge of Li-ion battery

Outline

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3 Novel Thermal Management Strategies

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Sources of Heat Within Cell

- 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 generated within 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.

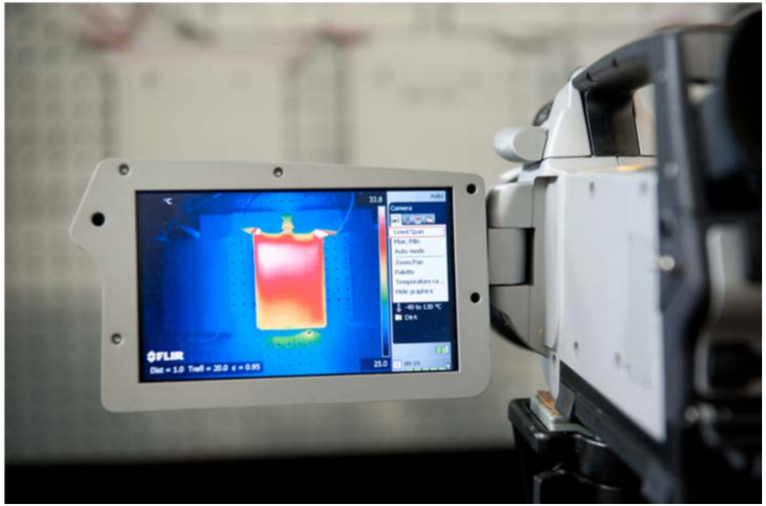
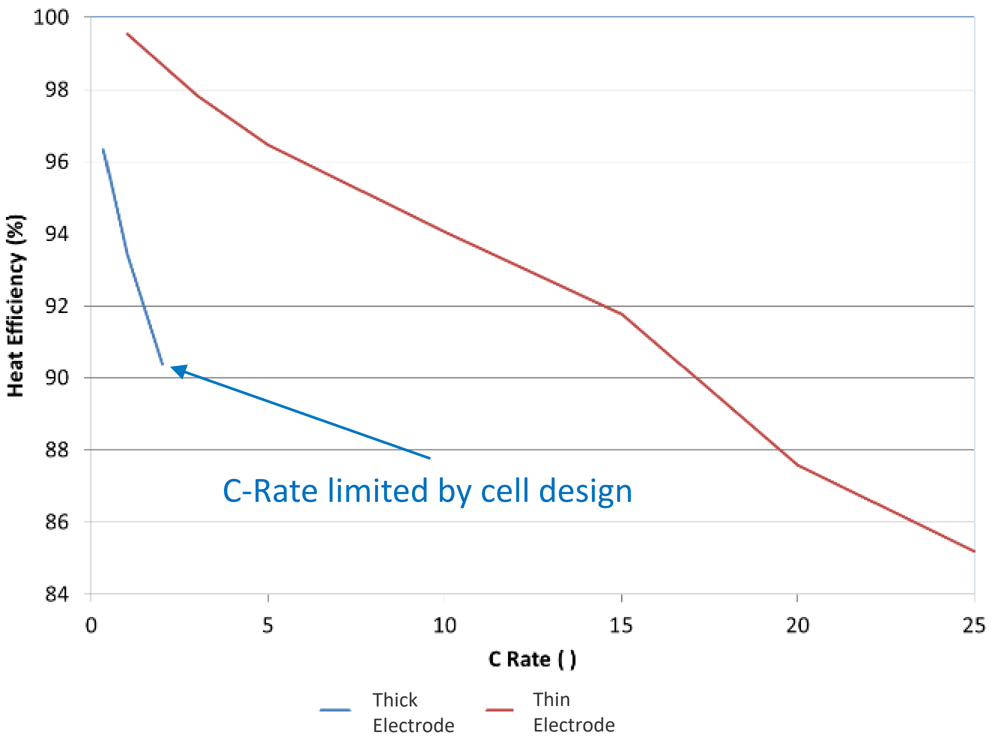


Photo by Aron Saxon, NREL

Electrode Thickness Impact on Efficiency

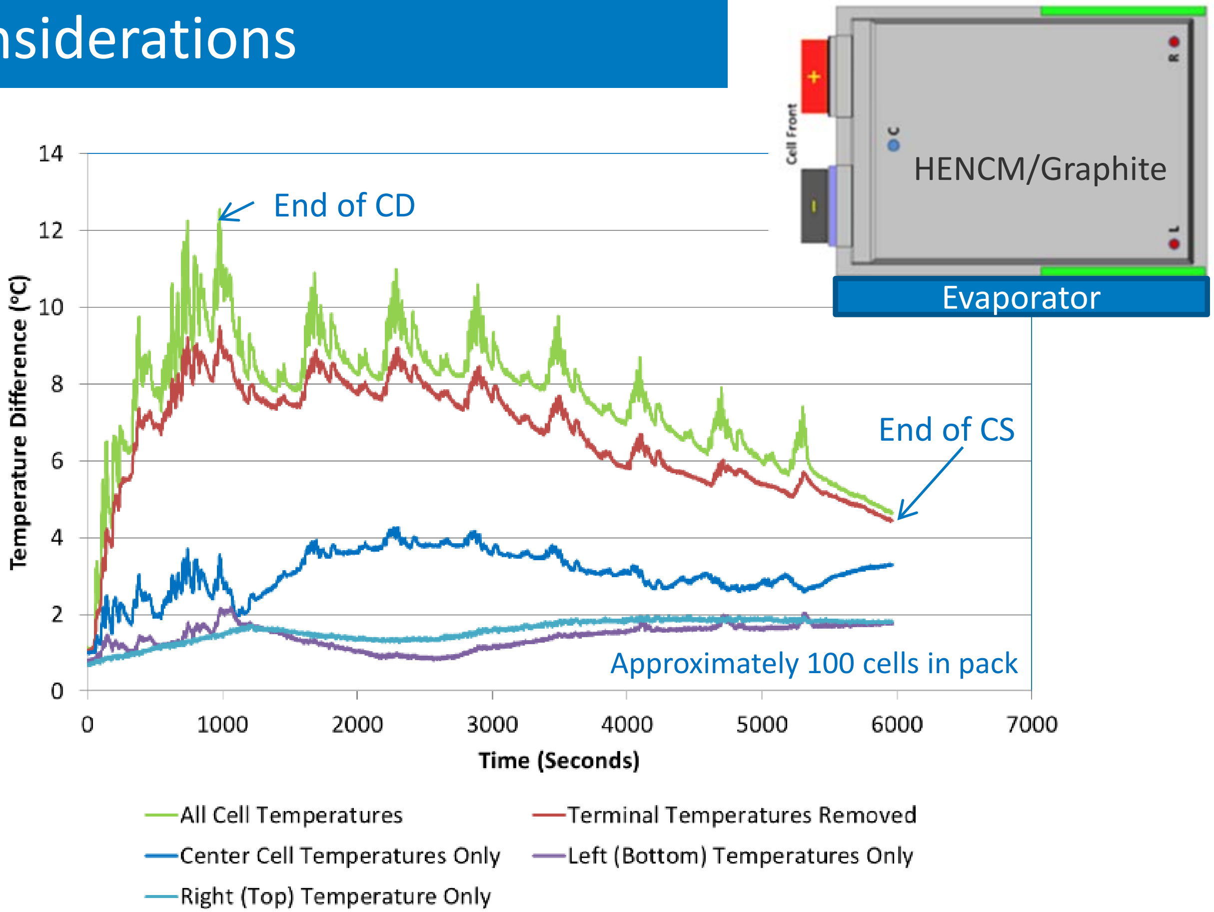
High energy density in today's battery chemistry relates to high electrode loading. Increasing the loading increases joule heating within the cell.



C-Rate limited by cell design

Active Thermal Management Design Considerations

Intercell heterogeneity must be considered when designing thermal management systems.



End of CD

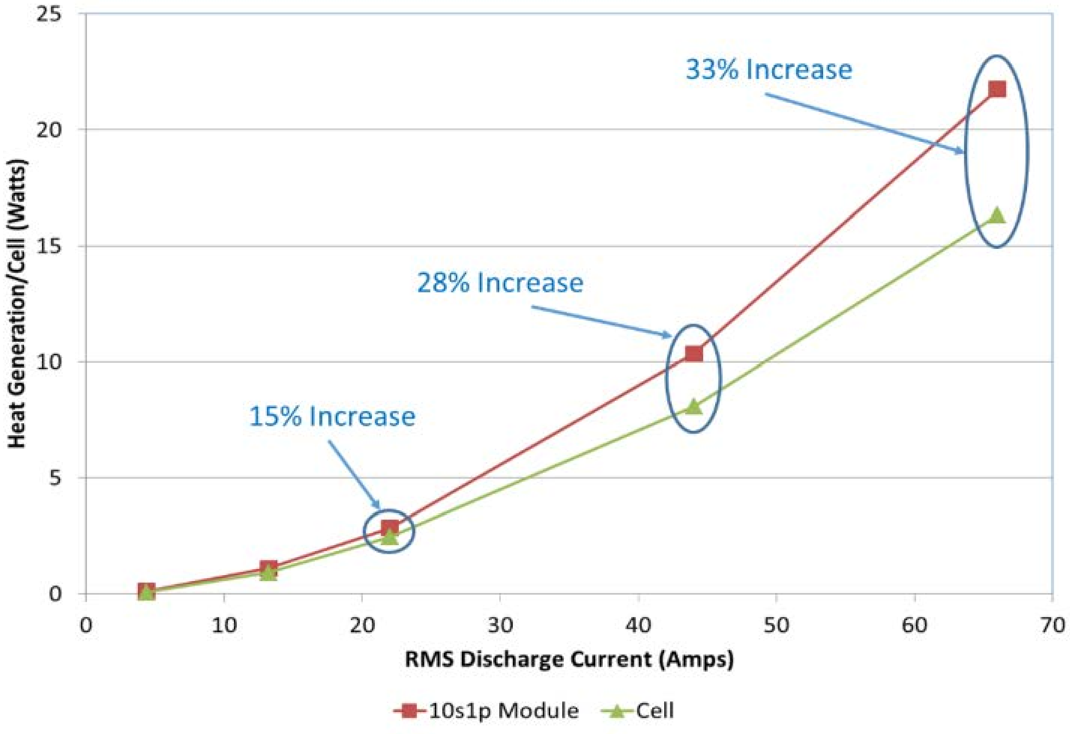
End of CS

Approximately 100 cells in pack

CD = charge depleting CS = charge sustaining HENCM = high energy nickel manganese cobalt

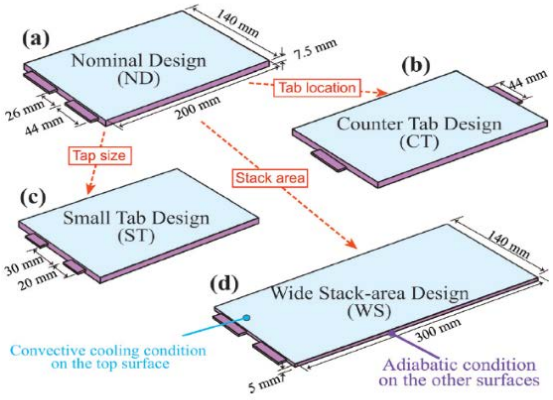
Heating from Pack Interconnect Design

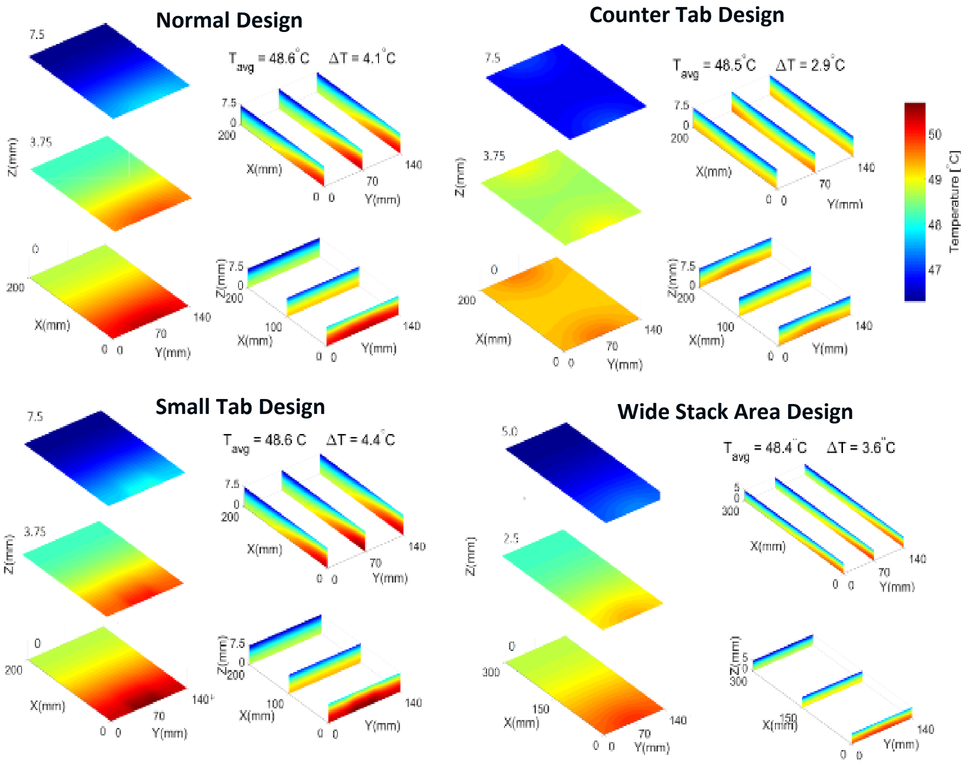
Under XFC the battery interconnect design will have added importance. Minimizing interconnects for cost reduction or weight saving could increase thermal load.



Cell Design and Temperature Variation

Cell design impacts thermal characteristics of cells and thermal management system design.




Normal Design

Counter Tab Design

Small Tab Design

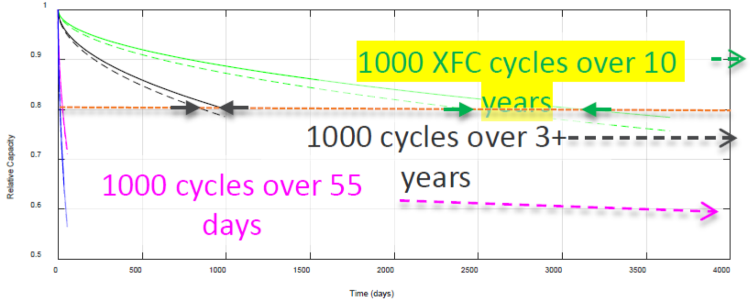
Wide Stack Area Design

Source: Keyser, Matt. 2017. “Thermal Implications for Extreme Fast Charge.” Presented at Vehicle Technologies Office (VTO) Annual Merit Review and Peer Evaluation, Washington, D.C.

Outline

Charging at 60°C to Mitigate Lithium Plating

When 1,000 cycles are spread over 10 years, the benefit of rapid cooldown (extends calendar life) increases to 20% longer life



1000 XFC cycles over 10 years

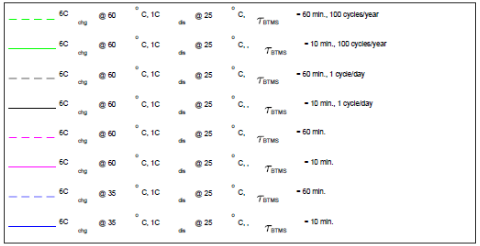
1000 cycles over 3+ years

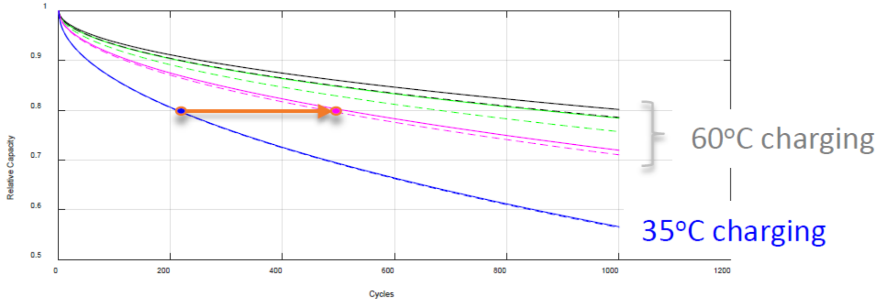
1000 cycles over 55 days

- 20% longer life
- 2.5% more capacity

- 17% longer life
- 1.5% more capacity

- 7% longer life
- 0.7% more capacity





60°C charging

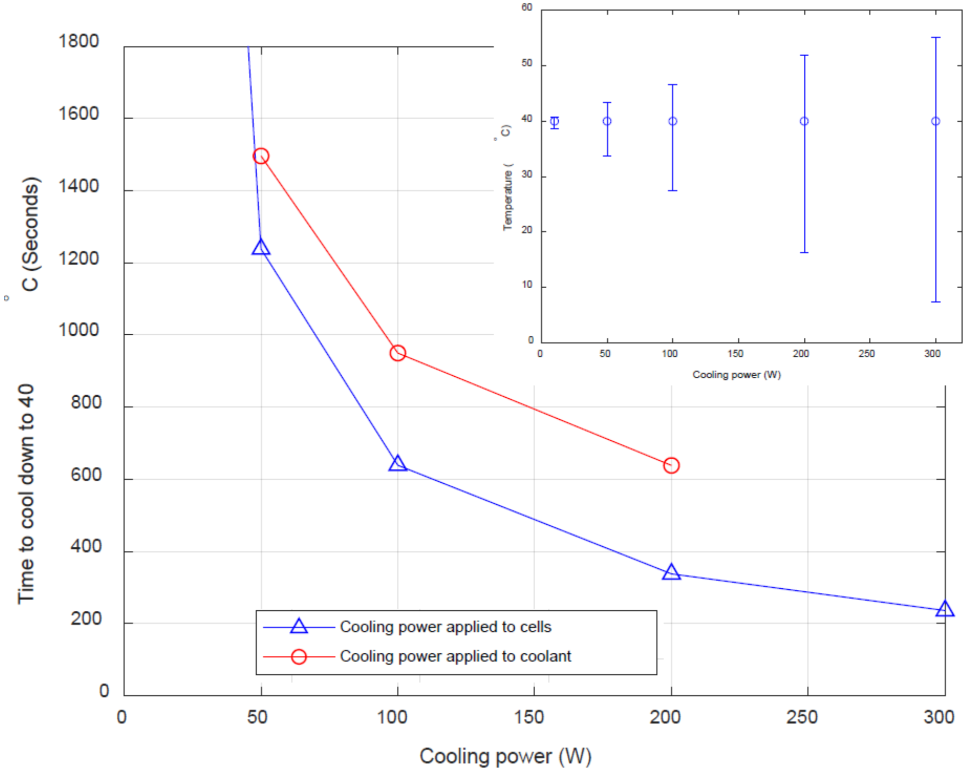
35°C charging

150% longer cycle life when XFC at 60°C vs. 35°C*

**Model accounts for cathode cracking and SEI/cathode electrolyte interface (CEI) growth, not Li plating. Li plating will also see benefits.*

Source: Keyser, Matt. 2017. "Thermal Implications for Extreme Fast Charge." Presented at Vehicle Technologies Office (VTO) Annual Merit Review and Peer Evaluation, Washington, D.C.

Charging at 60°C to Mitigate Lithium Plating

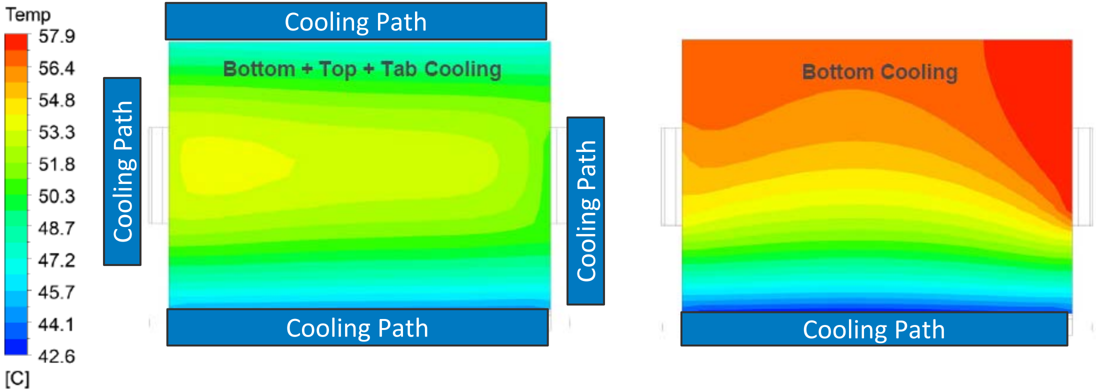


- For a Chevy Bolt size pack, it will require about 12 kW to cool the pack in 10 minutes when the cooling power is applied directly to the cells. The pack cooling capacity will need to double, 24 kW, if the heat goes through a bottom cold plate.
- With a bottom cold plate removing heat from cells, a large temperature difference will result with higher cooling capacities. This can be improved by optimizing heat dissipation paths.
- Cooling performance is affected by various design factors including cell thermal conductivity, thermal resistance along cooling pathway, and arrangement for surface cooling.

Source: Keyser, Matt. 2017. “Thermal Implications for Extreme Fast Charge.” Presented at Vehicle Technologies Office (VTO) Annual Merit Review and Peer Evaluation, Washington, D.C.

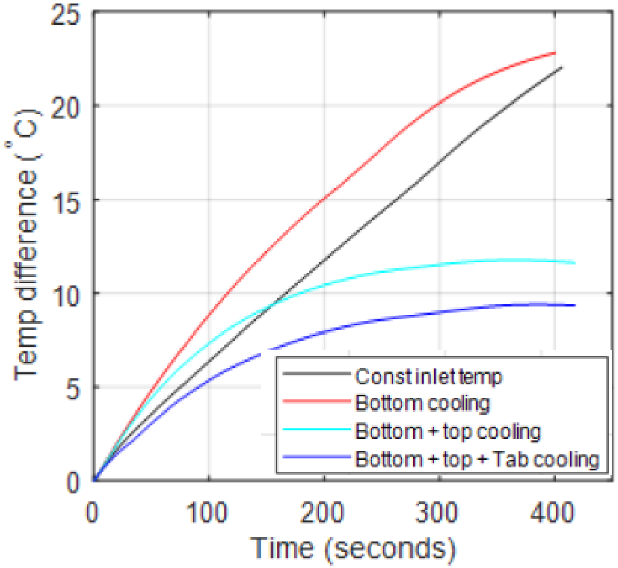
Increasing Cooling Paths Within Pack Design

Bottom cooling only: 22°C ΔT
Bottom and top cooling: 12°C ΔT
Bottom, top, and tab cooling: 9°C ΔT



Temperature contours of a cell cross section after 250 seconds under a 6C charge.

Temperature Variation Under Four Cooling Strategies

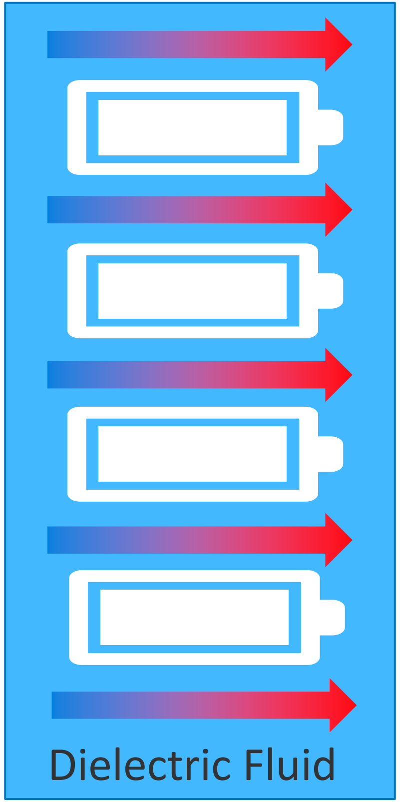


Constant inlet temp is constant temperature air boundary condition

Source: Keyser, Matt. 2017. “Thermal Implications for Extreme Fast Charge.” Presented at Vehicle Technologies Office (VTO) Annual Merit Review and Peer Evaluation, Washington, D.C.

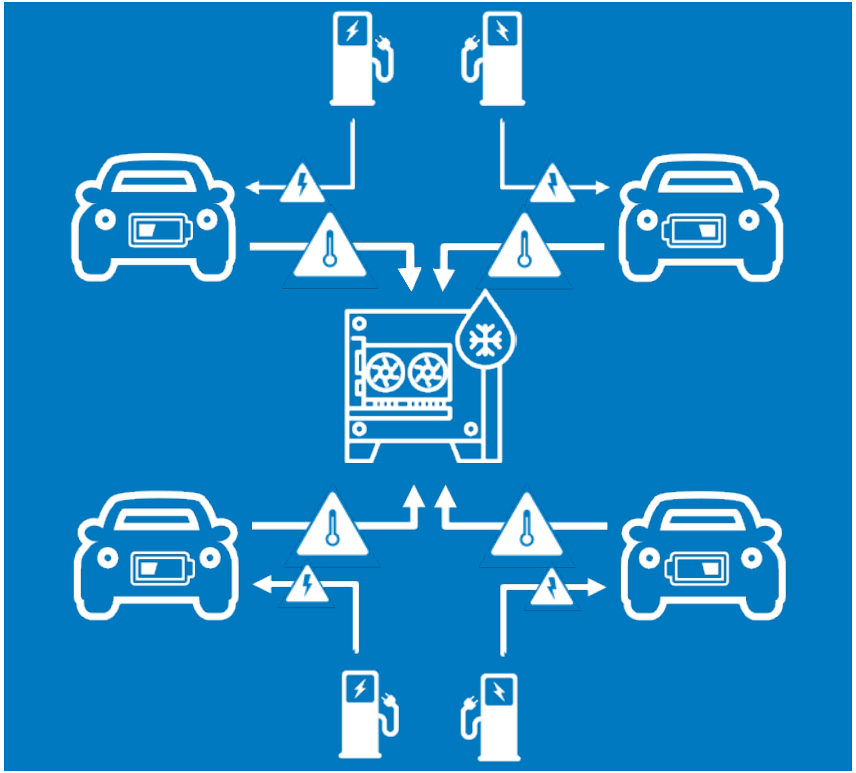
Immersion Thermal Management

Surrounding battery in pumped dielectric fluid to maximize the heat flux out of the cell and transferred to a rejection point (condenser in an actively cooled system).



Off-Vehicle Thermal Management

- Provide supplemental central cooling during fast charge.
- Pump cooling fluid through charge tether.
- Minimizes on vehicle thermal management system.



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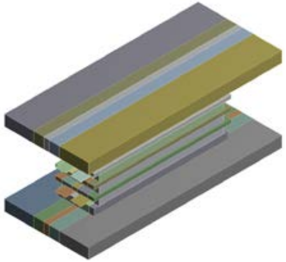
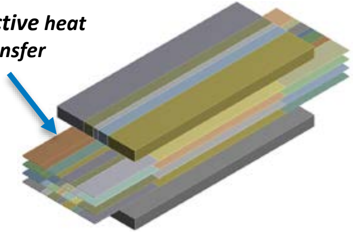
Heat Absorption with Aluminum Heatsinks

Tests done by BATlab in Sandia National Laboratories

Case A1 (testing)

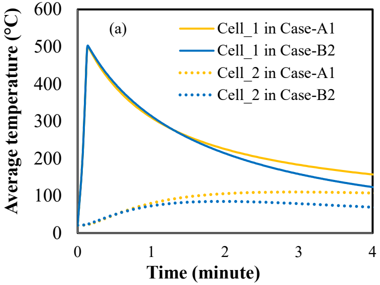


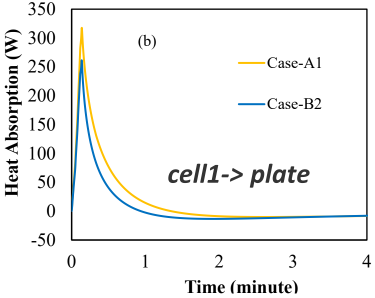
Case B2 (modeling)

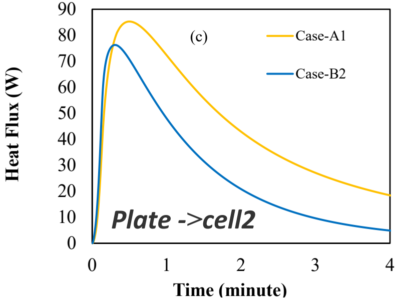


Case	A1	B2
Fin thickness, mm	3.2	0.8
Surface area, m^2	5.05e-3	2.02e-2

$$\int_{t1}^{t2} q_{TR}dt = (mC_p\Delta T)_{trigger\ cell} + (mC_p\Delta T)_{Al\ plate} + (mC_p\Delta T)_{neighbor\ cells} + \int_{t1}^{t2} q_{cooling}dt$$



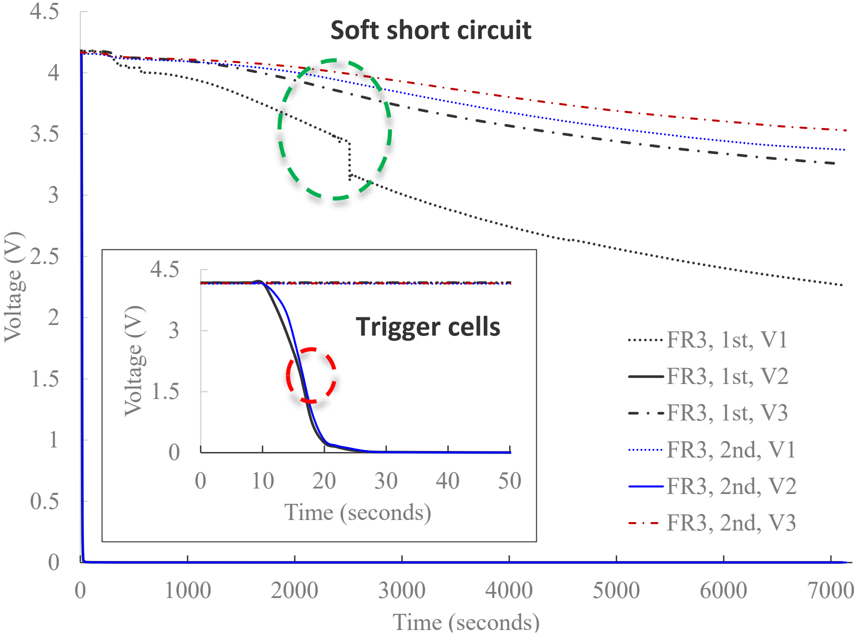




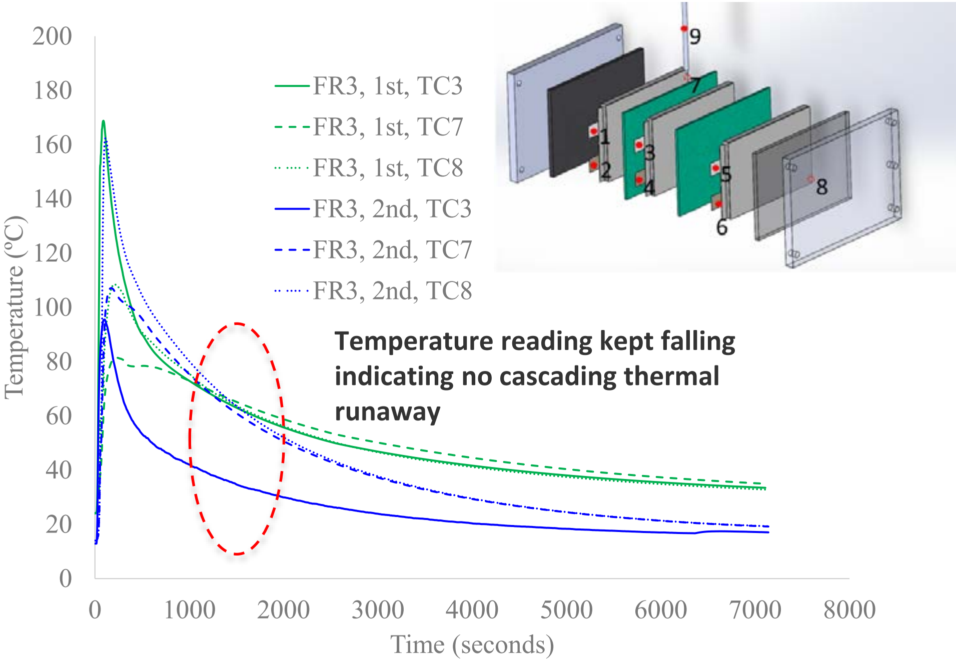
- Passive management with Al fins among cells
- TR propagation prevented In both cases
- Aluminum fin optimized to enhance heat dissipation.

Source: Yang, Chuanbo. 2021. "Thermal Management Methods for Mitigating Thermal Runaway Propagation in Li-Ion Battery Systems." Presented at International Battery Seminar & Exhibit.

Flame Retardant Foams to Avoid Thermal Runaway Propagation



Soft short circuit



Temperature reading kept falling indicating no cascading thermal runaway

- Soft short circuit occurred in neighboring cells
- Heat released by neighboring cells insignificant, indicating cascading TR prevented.

FR3: Fire-Retardant 3

Source: Yang, Chuanbo. 2021. "Thermal Management Methods for Mitigating Thermal Runaway Propagation in Li-Ion Battery Systems." Presented at International Battery Seminar & Exhibit.

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Conclusions and Outlook

- Robust battery thermal management will be required to make XFC a reality—even with high-power cells, an oversized battery thermal management system is needed.
- Fast charge at high temperature - 60°C - is a strategy that can increase fast charge longevity by minimizing lithium plating.
- 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.
- Coupling cell design and cooling strategy will have an impact on the temperature variation within the cell and the temperature imbalance within the pack.
- New thermal management strategies like dielectric fluid immersion may be needed to keep the battery within operational temperatures and minimize temperature variation within the system.
- Centralizing the heat rejection to a station chiller could alleviate the need for the vehicle to have a thermal management system capable of keeping up with fast charge.
- Thermal runaway propagation can be avoided by:
  - Removing heat quickly from a cell undergoing failure – through the introduction of aluminum heat plates and fins (or advanced cooling techniques).
  - Providing insulation in the form of fire-retardant foam.

NREL
Transforming ENERGY

Acknowledgements

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USABC
UNITED STATES ADVANCED BATTERY CONSORTIUM

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Thank You

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www.nrel.gov/transportation/energy-storage-thermal-mgmt.html

NREL/PR-5700-84463

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