Development of a Safe, Lightweight 28V/25Ah Li-ion Battery for Navy Aircraft F/A-18E/F Super Hornet

By

Dr. Trung Hung Nguyen of EIC Labs.,
Dr. Ahmad Pesaran and Dr. Chuanbo Yong of NREL

Chris Derby and Mark. Hurley, of NAVAIR, Terry Meriweather of NSWC Crane,
Dr. Venkatesan Manivannan and Chuck Singer of NAVAIR

Presented at

Joint Service Power Expo, May 2-3, 2017, Virginia Beach, VA

EIC Laboratories

Development of the F/A-18E/F Aircraft Main Battery

1. Battery is an important component of the aircraft DC power system

2. Battery can be used aboard the aircraft for auxiliary power unit starting, canopy operation, refueling, lighting, emergency power, flight control backup

3. EIC is working with NAVAIR to develop safe 28V/25Ah Li-Ion battery as a drop in replacement for current SLAB used on the F/A-18E/F Super Hornet aircraft

4. The F/A-18E/F aircraft has two 150-amp transformer-rectifiers (TRs), one 50-amp battery charger and one 15.0 Ah sealed, lead-acid (SLA) aircraft battery

5. Battery would have to survive a random vibration level of 7.7 Grms over a frequency range of 10 - 2000 Hz and sinusoidal vibration levels of up to 10.0 Gs over a frequency range of 50 - 2000 Hz

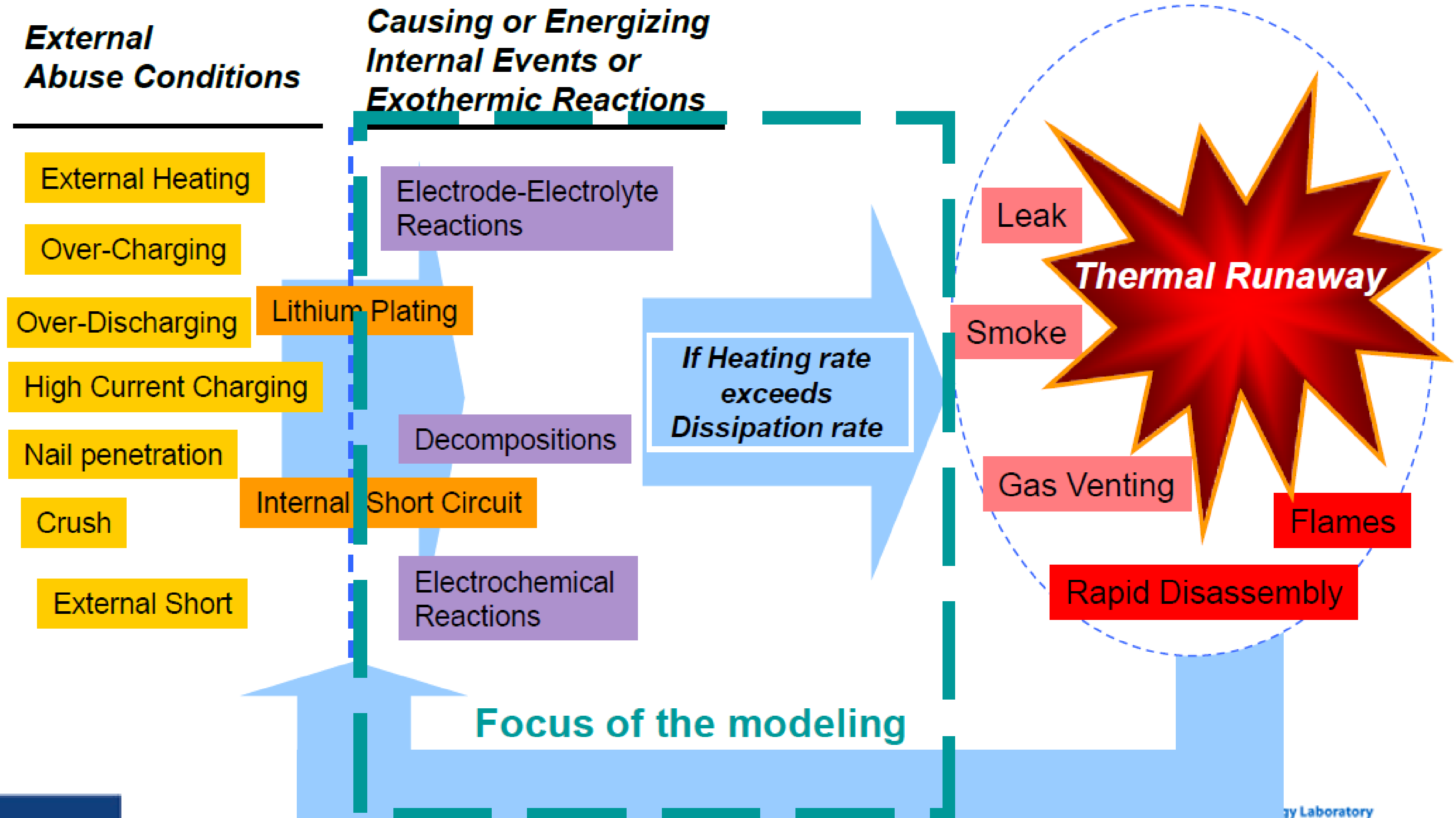
EIC Laboratories

Overview of Li-Ion battery Safety

- Li-Ion battery contains no metallic lithium in its elemental form
- Have twice the energy of a nickel-based battery and four-times that of lead acid
- Low maintenance system with no memory effect
- However, under abuse operating conditions, Li-Ion cells can generate large amount heat that could possibly lead to thermal runaway

EIC Laboratories

NREL Thermal Runaway - Background



" Thermal Abuse Modeling of Li-Ion Cells and Propagation in Modules", *Gi-Heon Kim, Ahmad Pesaran, and Kandler Smith at NREL*, presented at 4th International Symposium on Large Lithium-Ion Battery Technology and Application (May 2008)

Approaches in Mitigating Thermal Runaway Reactions

- Safety is the primary criterion in EIC Li-Ion battery pack's design and architecture

- EIC approaches to develop Safe Li-Ion Battery System:

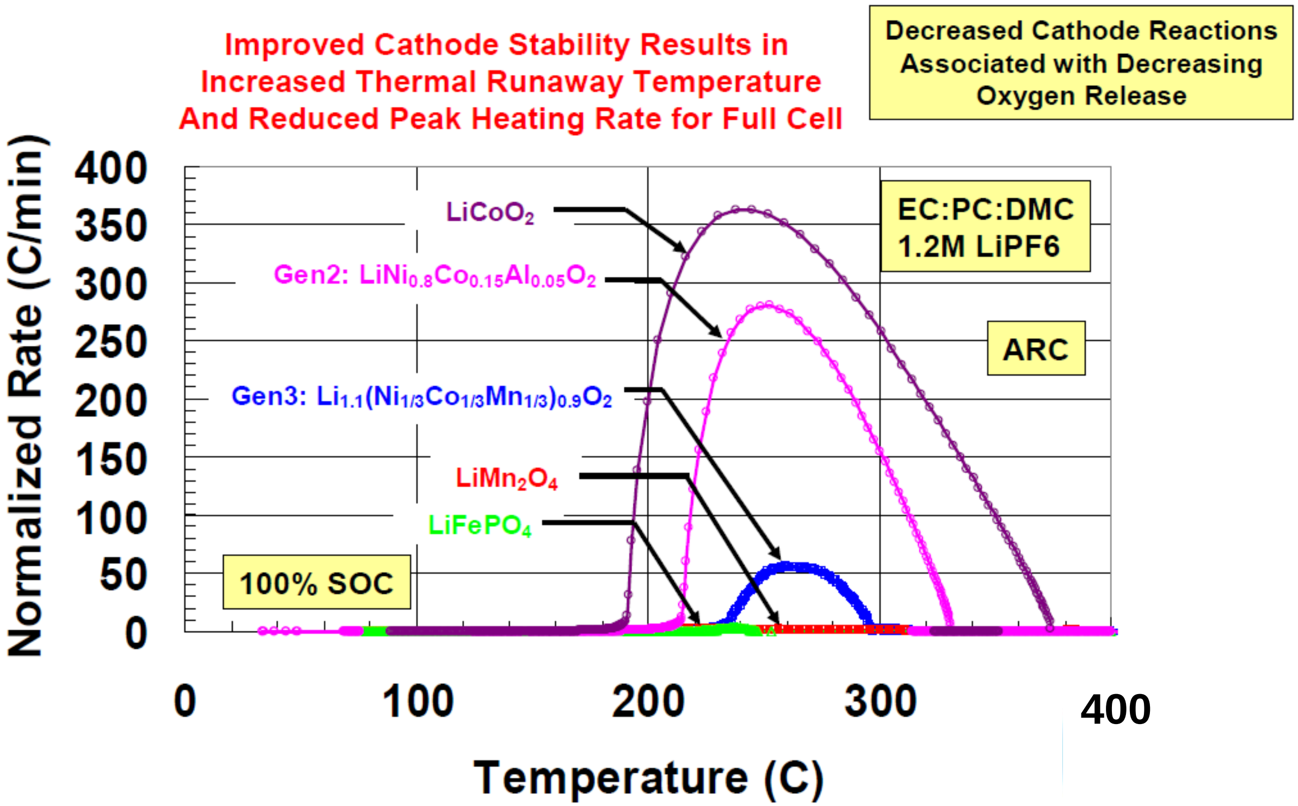
1. Select highly stable cathode chemistry to minimize heat generation

2. Modular battery design Architecture

3. Design and integrate electronic circuits to control the safe operation of the battery

EIC Laboratories

Heat Generation of Cathode Materials



“Critical Cell Properties Affecting Abuse Tolerance: Cathode Chemistry and Separator Integrity,” E.P. Roth et.al., presented at Large Lithium Battery Tech. and Appl. Symp., Long Beach, CA, June 8-12, 2009 s

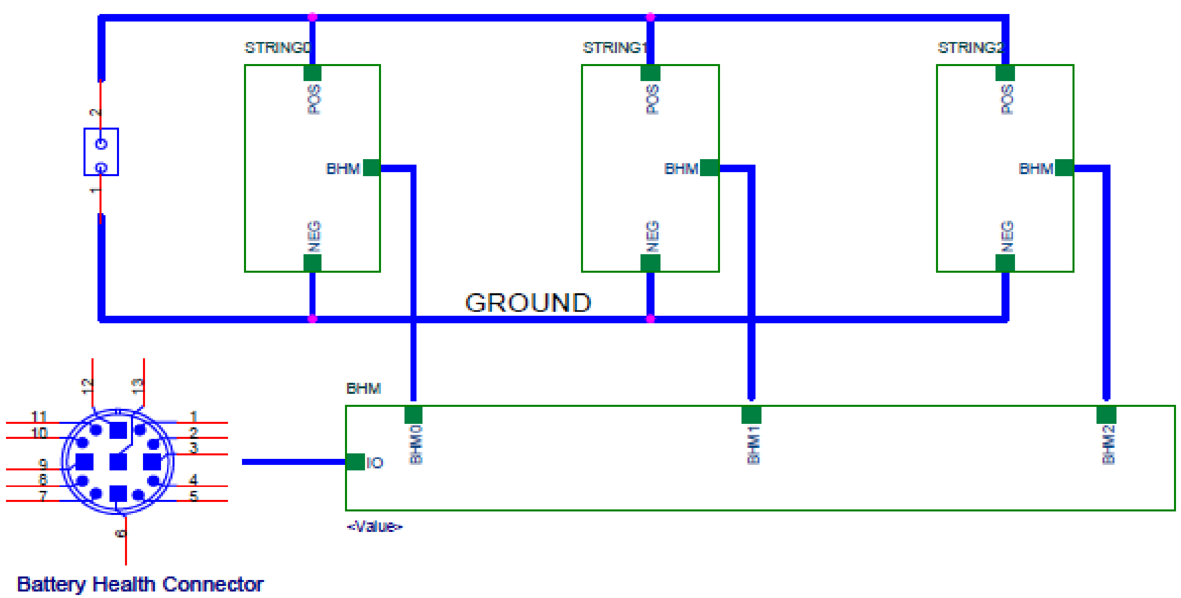
Battery Management System (BMS)

- Lithium-ion system is safe, providing certain precautions are met when charging/discharging
- Battery has to operate within operating voltage limits
- BMS continually monitors voltage, currents, and temperatures within the pack
- BMS protects the battery against adverse safety conditions such as overcharge, over-discharge, short circuit, and high temperature

EIC Laboratories

EIC Modular Battery Design Architecture

1. Modular approach in designing battery system
2. Each module has its own independent BMS circuit
3. Batteries are designed by connecting modules with BMS in parallel
4. Battery Health Monitoring (BHM) unit connects to each individual battery BMS and receives status information from each unit.



Laboratories

1st Generation of Safer Li-Ion Battery Design for NAVAIR Aircraft Platform

Current "Safer Li-Ion Battery" relies on

1. Safe LFP cathode chemistry

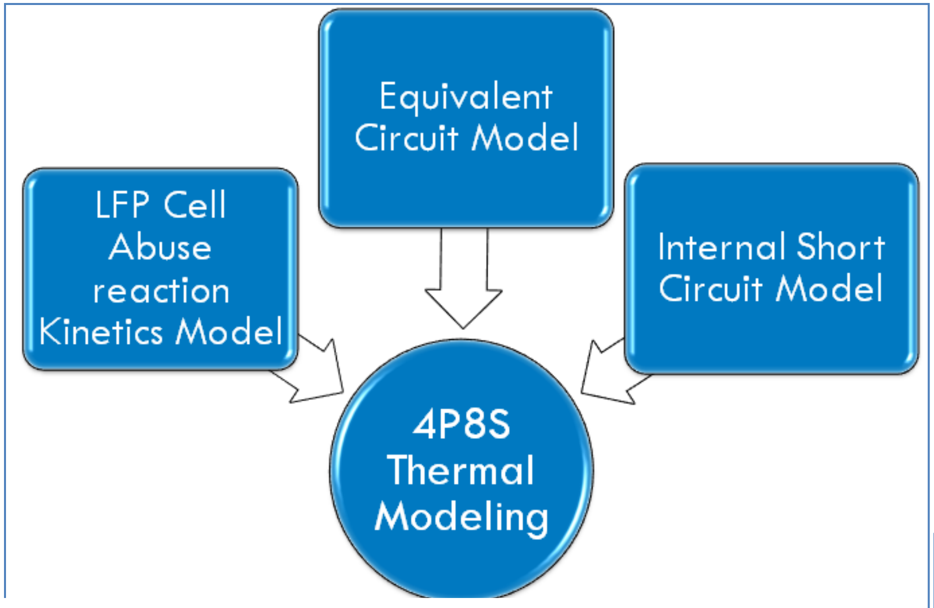
2. Small 2.5Ah A123 cylindrical26650 cells

3. Modular battery design using 10Ah module with 2.5Ah cells in 4P8S configuration with Flame-Retardant foam in between cells

4. Thermal modeling to evaluate, when one individual cell develops thermal instability, if heat propagation to neighboring cells can trigger thermal runaway

EIC Laboratories

NREL Thermal Modeling of 4P8S Battery Module



A123 2.5 Ah ANR26650 M1 cylindrical cell	
Capacity (Ah)	2.4
Weight (g)	76
Density (kg/m^3)	2264
*Cp (J/kgK)	855
*k (w/mK) (Radial, Tangential and Axial)	(0.8, 27, 27)

Thermal properties of A123 M1 cell

Flame Retardant Foam	
Density (kg/m^3)	20
*Cp (J/kgK)	1450
*k (w/mK)	0.038
Thermally stability	-55^{0}C to 100 ^{0}C

Thermal properties of flame retardant material

Case 1: One cell goes into thermal instability with cell temperature at 600^{o}C

Case 2: Cathode-anode type short-circuit due to separator breakdown in one cell

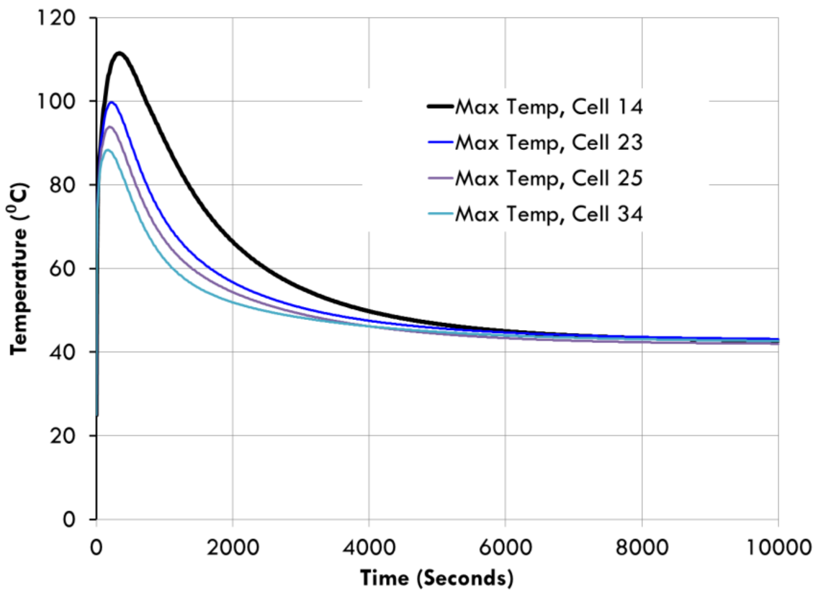
Case 3: One cell develops internal short. The three neighboring cells dump circulating current of about 400A to the shorted cell

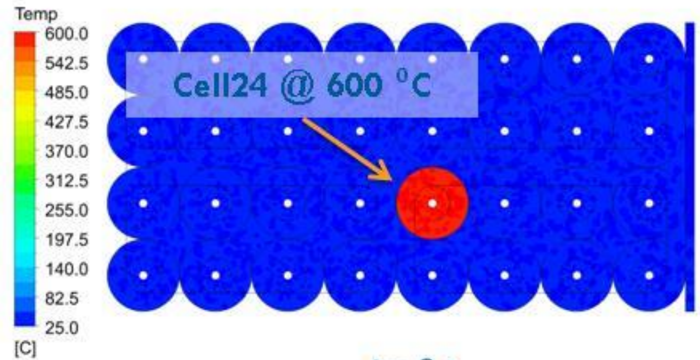
Case 1 Thermal Modeling Results

1. In this study, initial temp of the cells except cell 24 was 25 ^{0}C. Thermal event occurred within cell 24 and initial temperature of cell 24 is 600 ^{0}C.

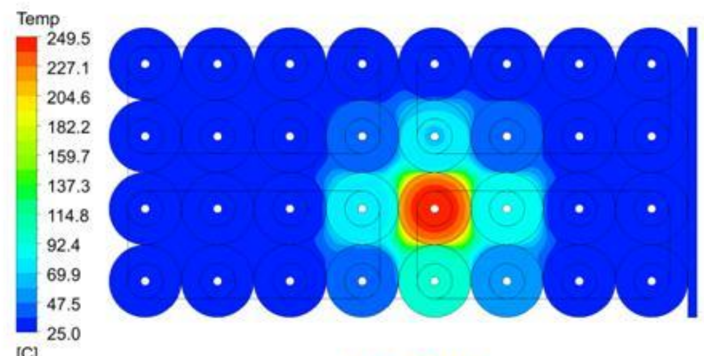
2. Thermal modeling results show that other cells remain below 120 ^{0}C and thus safe

3. This study indicates a single external cell failure in the 4P8S module most likely will not produce a cascading failure event

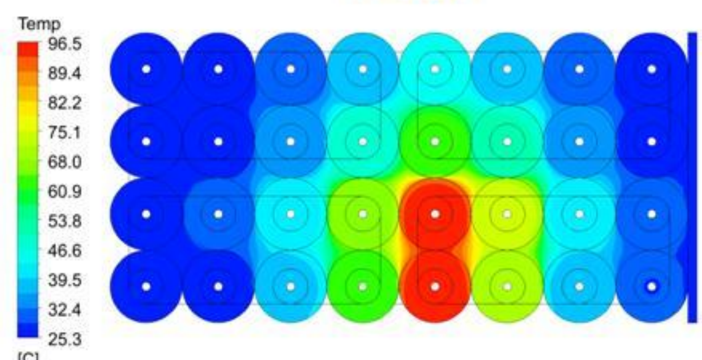




t = 0 s



t = 300 s

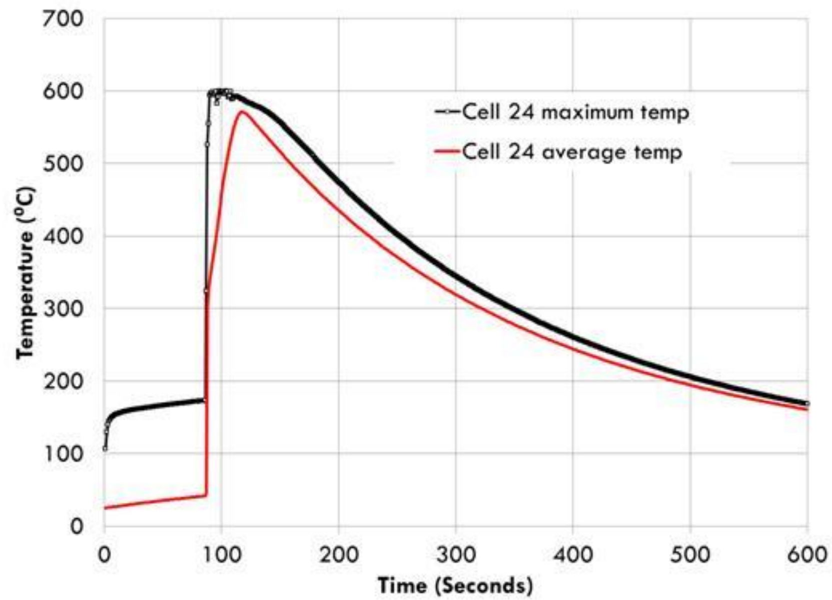


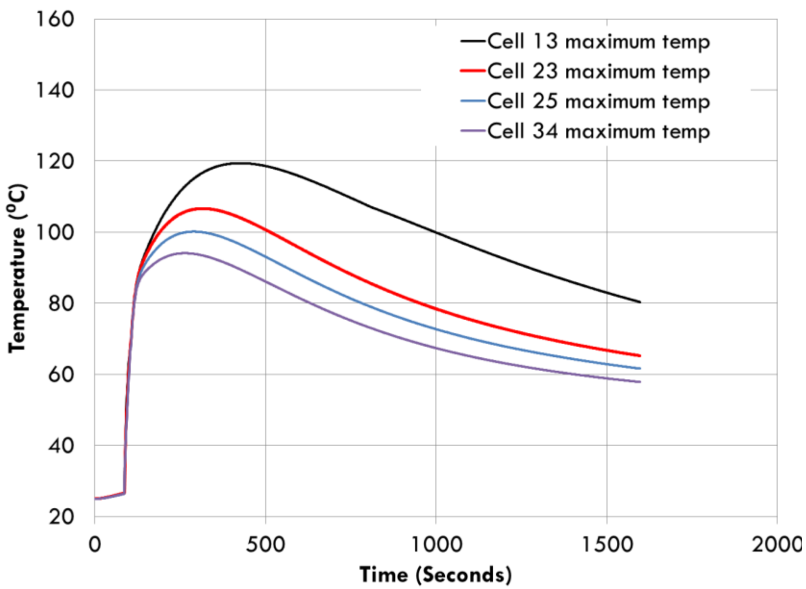
t = 900 s

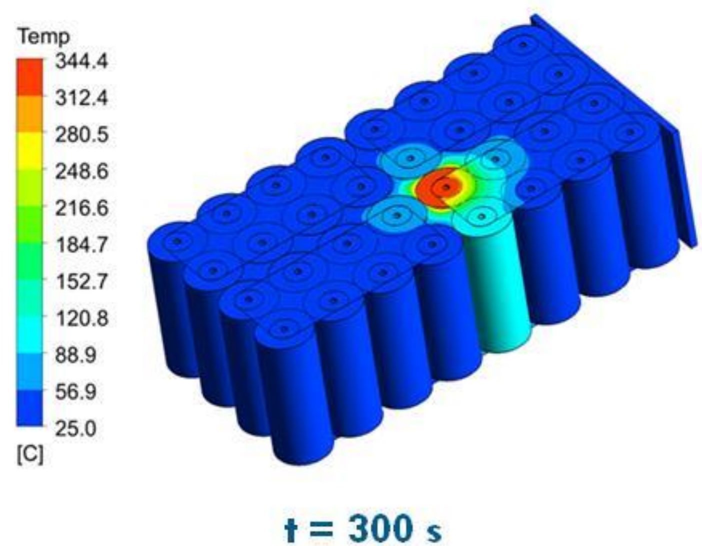
EIC Laboratories

Case 2 Thermal Modeling Results of 4P8S Module

1. Cathode-anode type short circuit occurs in cell 24 of the 4P8S module; Short-circuit growth due to separator breakdown.
2. Cell 24, went into full thermal runaway in about 2 minutes with max temp of 600^{o}C.
3. Results show maximum temperatures of other cells were less than 140 ^{0}C
4. Study indicates a single external cell failur
will n
even

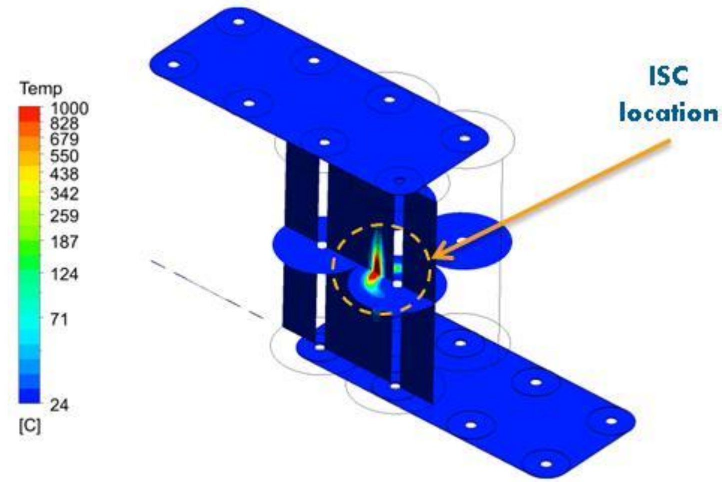




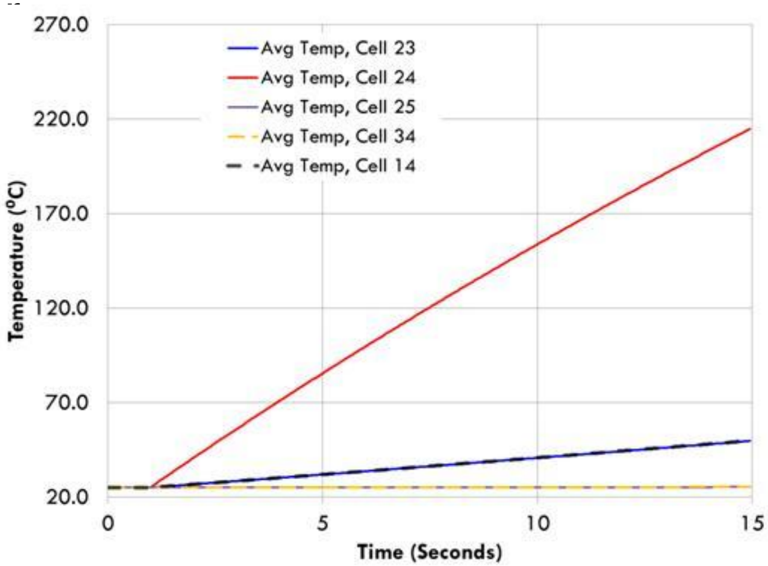


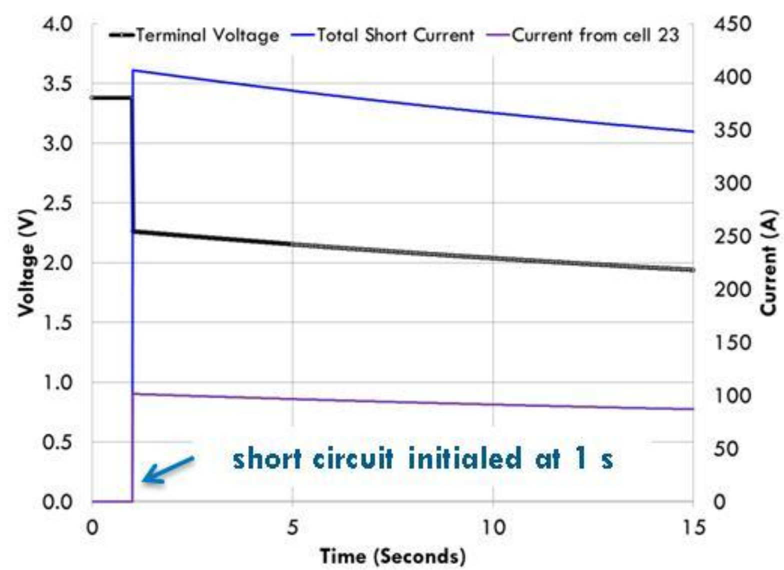
Case 3 Thermal Modeling Results of 4P8S Module

1. Cell 24 in the 4P group develops an internal short. The circulating current from the other 3 into the short cell is about 400 A
2. Hot spot in cell 24 where short-circuit locates was more than 1000 ^{0}C after about 1 second due to the circulating current joule/resistive heating
3. Compared with internal temperature rise, external temperature rise was relatively slow
4. Neig



Internal temp contour at 1.98s

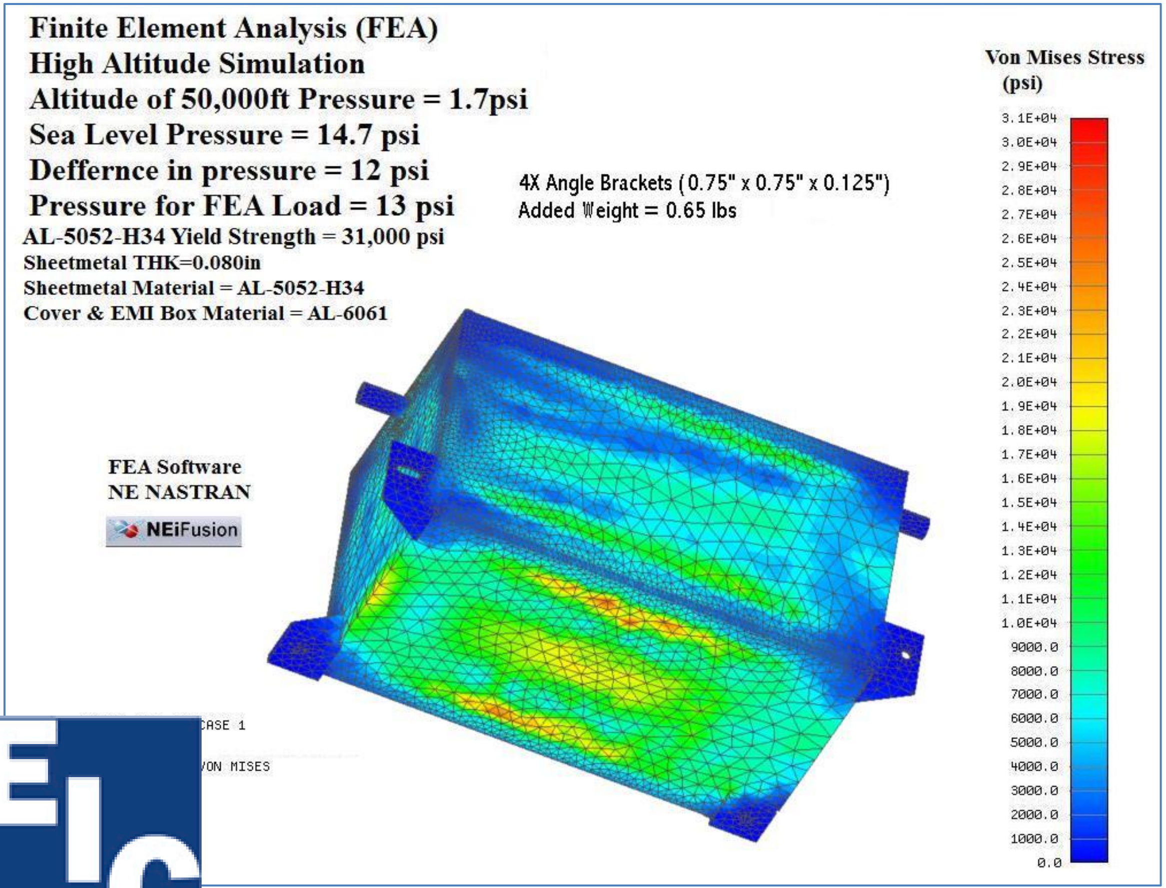




EIC Laboratories

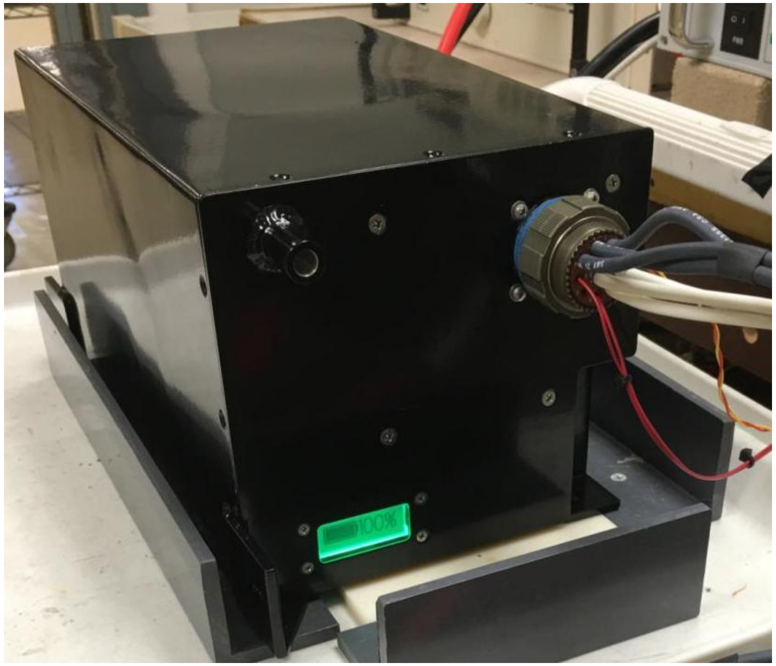
EIC 28V/25Ah Li-Ion Battery Case Design

1. Battery case designed to withstand the high altitude flight of the F-18 aircraft
2. **Finite element analysis** (FEA) used to ensure the battery works at 50,000 feet
3. Prototype F-18 battery submitted to high altitude storage test at 50,000 feet inside walk-in altitude chamber for 30 minutes to confirm battery integrity and FEA results

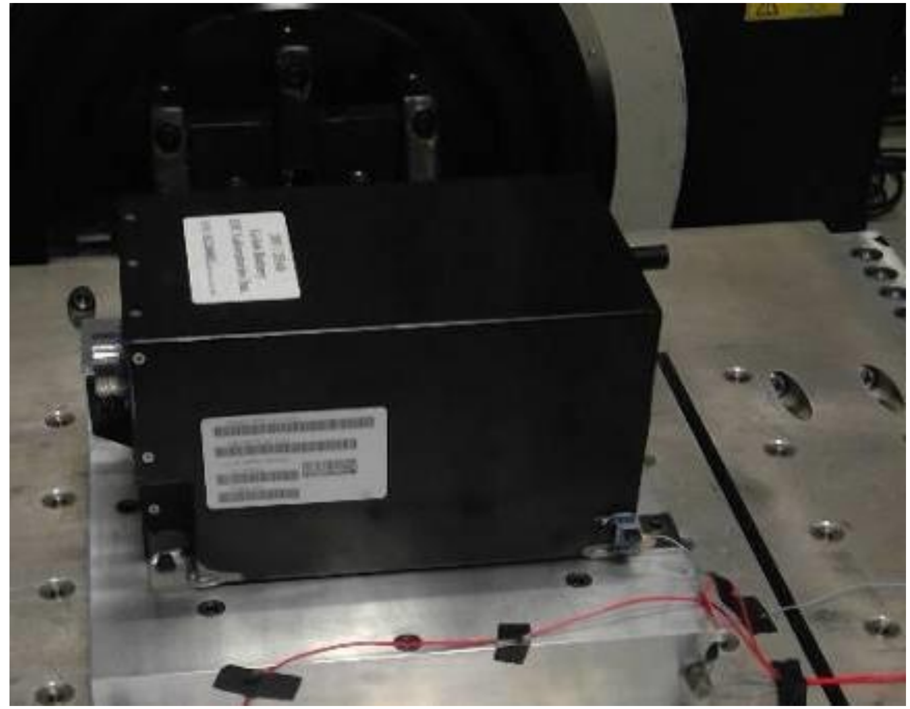


Battery inside high altitude storage chamber

EIC 28V/25Ah Li-Ion Battery Shock and Vibe Test



EIC 28V/25Ah battery with State of Charge LCD display and RS-485 battery Diagnostic Output



EIC 28V/25Ah battery has passed
1- EMI MIL-STD 461F
2- Aircraft mechanical Shock and Vibration tests
3- Aircraft Electric Power Characteristics MIL-STD 704F

EIC Laboratories

EIC 28V/25Ah Battery Performance Testing at NAVAIR

BASELINE CAPACITY CHECK (1C-RATE 26A) TRU Interoperability	Cha (Ah)	Dis (Ah)	Pass
Discharge 25A to 20V (BATT2)		25.33	✓
50AMP TRU-2 Re-Charge	25.44		✓
Discharge 25A to 20V (BATT2)		25.3	✓
50AMP TRU-2 Re-Charge	25.36		✓
CAPACITY DISCHARGE AT Various C-Rate (-2 TRU)			
Discharge 10A to 20V		25.2	✓
50AMP TRU-5 Re-Charge	25.32		✓
Discharge 20A to 20V		25.02	✓
50AMP TRU-5 Re-Charge	25.13		✓
Discharge 30A to 20V		25.06	✓
50AMP TRU-5 Re-Charge	25.15		✓
Discharge 40A to 20V		25.02	✓
50AMP TRU-5 Re-Charge	25.12		✓
Discharge 50A to 20V		25.29	✓
50AMP TRU-5 Re-Charge	25.33		✓
MAX CAP Discharge TEST			
DC PS CHG 28.9V 50A CL	0.03		✓
Discharge 25A to 20V		25.4	✓
50AMP TRU-5 Re-Charge	25.48		✓
AIRCRAFT TURNAROUND LOADS			
AIRCRAFT TURNAROUND LOADS DIS *AMBIENT*		4.42	✓
25A DIS to 20V to ID remaining Capacity		20.75	✓
50AMP TRU-5 Re-Charge	25.18		✓
AIRCRAFT START-UP LOADS			
AIRCRAFT START-UP LOADS Battery *AMBIENT*		3.1	✓
25A DIS to 20V to ID remaining Capacity		22.35	✓
28.5V 50A CL CHG -5 TRU	25.56		✓
AIRCRAFT EMERGENCY LOADS			
71A Discharge for 4.0 Minutes		4.76	✓
25A DIS to 20V to ID remaining Capacity			
28.5V 50A CL CHG (DC PS)	25.02		✓

Laboratories

Thank You

Acknowledgement

Funding from NAVAIR SBIR/STTR Program
and
TPOC: Dr. Venkatesan Manivannan

EIC Laboratories