Next Generation Lithium-Ion Cell Development and In-Orbit Performance

Next Gen Cell Development

EnerSys/Pyrotek/Forge Nano Collaboration Project Resulted in Technology Insertion on SMC Program, LEMUR2 for June 2021 Launch

EnerSys Gen 2.1 Chemistry
1.4Ah 18650 Cell, 118Wh/Kg
Non-Zero Volt Capable Cell
EnerSys Domestic Graphite/NCA Material

EnerSys Gen 2.2 Chemistry
1.4Ah 18650 Cell, 136Wh/Kg
Zero Volt Capable Cell
EnerSys Domestic Graphite/NCA Material

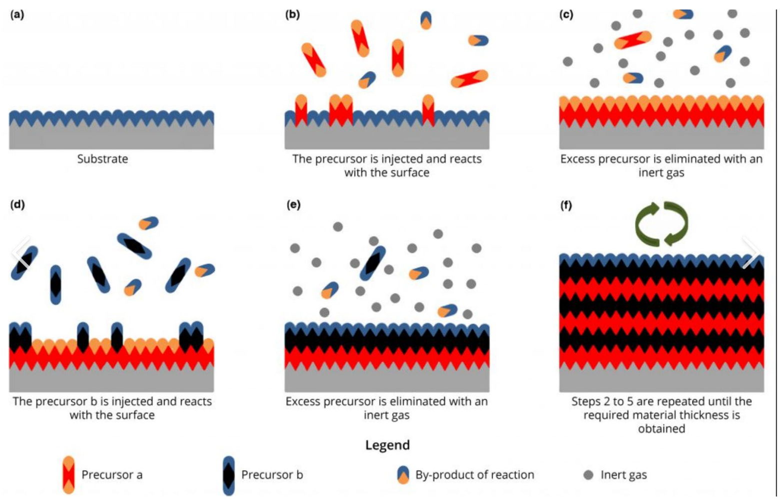
EnerSys Gen 3.0 Chemistry
2.4Ah 18650 Cell, 210Wh/Kg
Zero Volt Capable Cell
ALD Coated Pyrotek Domestic Graphite/Forge Nano NMC-811Material

EnerSys Gen 3.0 Zero Volt Chemistry Cells Delivered to Spire Global December 2020
June 2021 Falcon 9 Launch on 3-U Cubesat LEMUR2 Spacecraft
1st All Domestic Material Battery on Secure Space Program

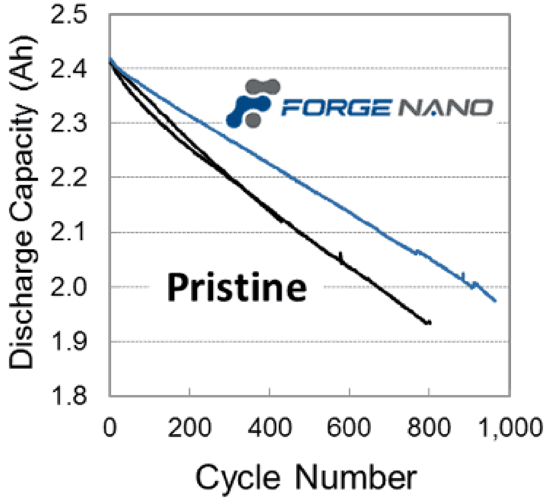
Forge Nano Atomic Layer Deposition

Atomic layer deposition (ALD) is a vapor phase technique used to deposit thin films onto a substrate.

The process of ALD involves the surface of a substrate being exposed to alternating precursors, which do not overlap but instead are introduced sequentially.



The use of Particle ALD or PALD to deposit simple and complex metal oxide nano-coatings around each tiny particle that makes up the powder coating on the anode and cathode electrodes in lithium-ion batteries is increasingly popular as it has been shown to improve the lifetime of the battery, increase the battery capacity and significantly improve safety.



www.forgenano.com for more information

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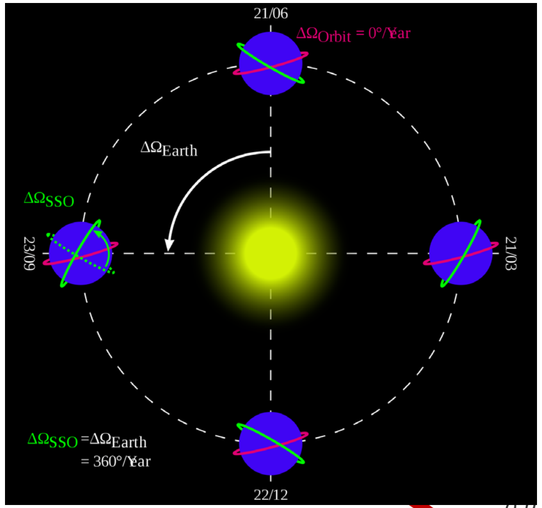
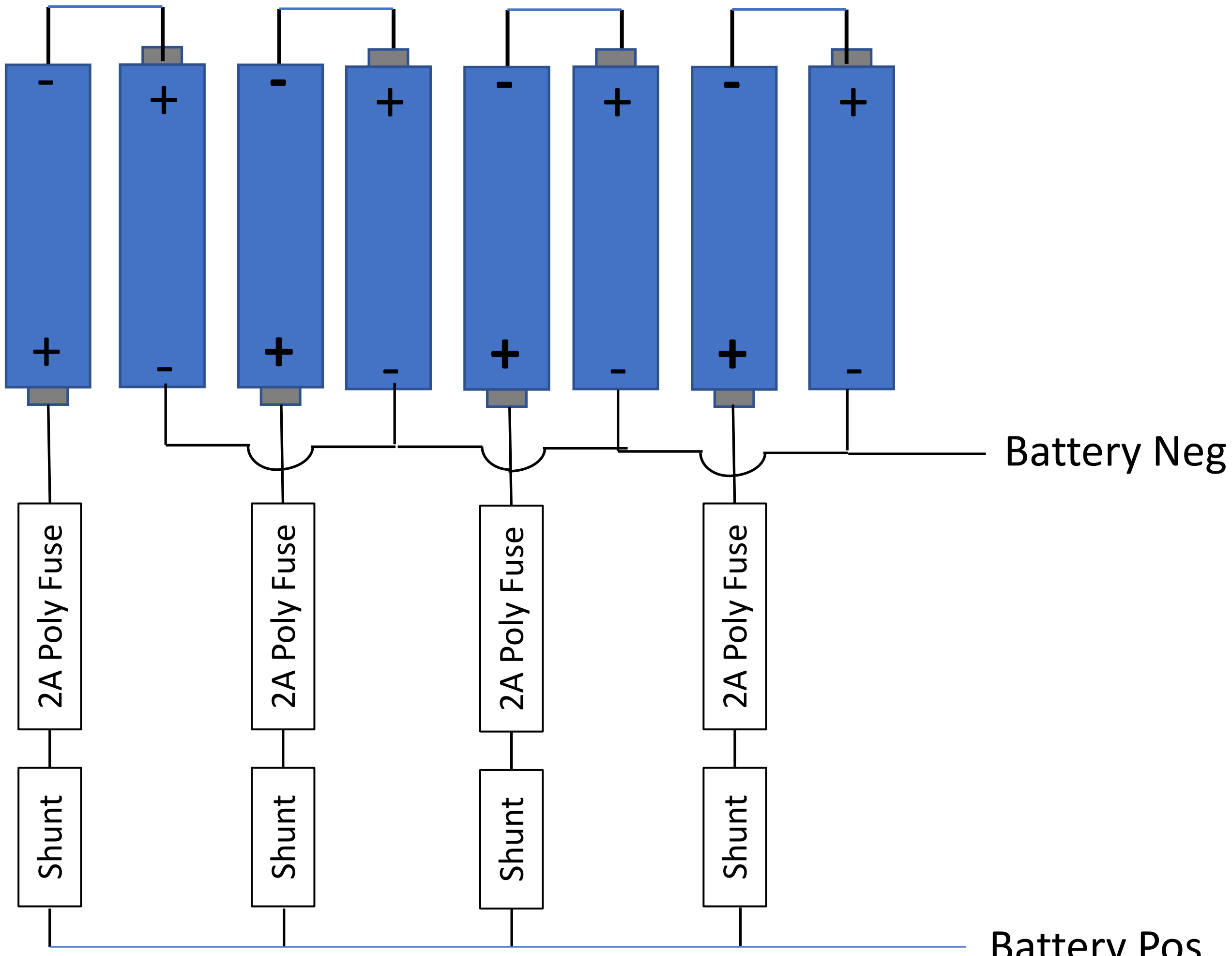
Lemur-2 Mission

- Space Force technology demonstration program
  - Demonstrate new innovative technology in a space environment
  - Payload technology was EnerSys/Pyrotek/Forge Nano Gen 3.0 Zero-Volt chemistry 18650 battery cells
    - Perform 20% and 40% DoD electrical cycling in-orbit
  - Battery cells delivered to Spire Global December 2020 for incorporation into spacecraft battery configuration (2S4P Battery)
    - 3-month cell development program
  - June 2021 Falcon 9 Launch on LEMUR2 Spacecraft
    - 550Km orbit, Sun-synchronous orbit
    - 13:30 Local Time at the Descending Node



Battery Configuration

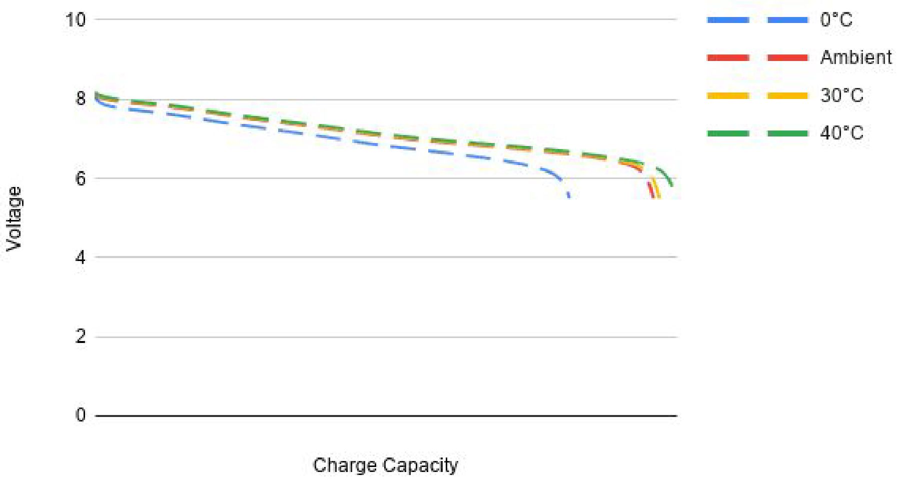
- 2S4P Configuration
- Measuring individual string current and Total battery voltage



Initial Battery Characterization

- 2S4P (~9.25Ah) Battery was subjected to reduced pre-launch qualification testing

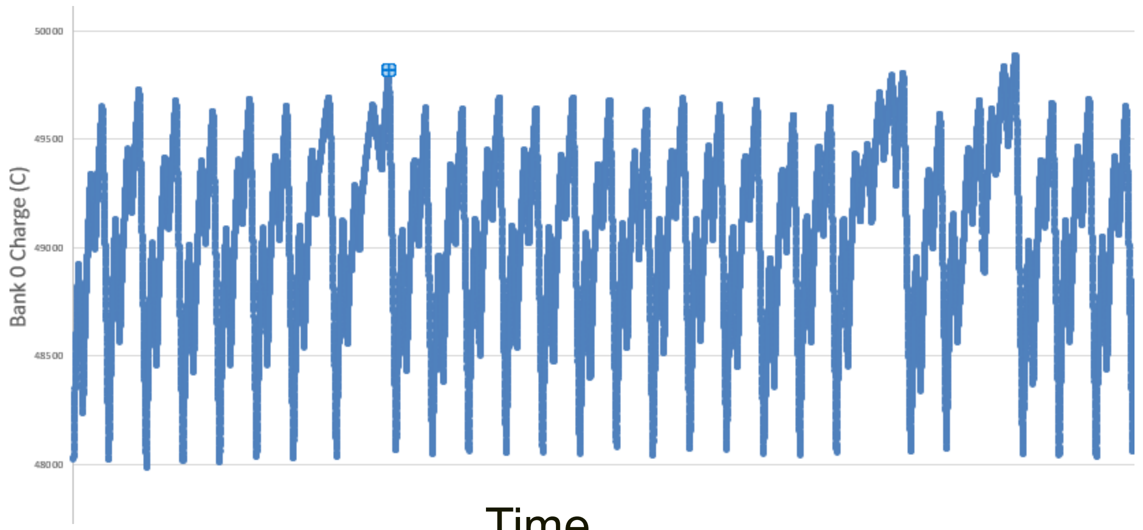
Discharge 1 - Nominal Discharge Rate



Test #	Test Type	Test Description
1	Inspection	Post-Build and Module Checkout
2 - 7	CDC	Various charge rates and temperature profiles
8	Inspection	Post-Thermal #1
9	Vibration Test	For axes in [Z, Y, X]: ● Resonance Search ● Sine Sweep ● Resonance Search ● Random Vibration ● Resonance Search
10	Inspection	Post-Vibration
11 - 12	CDC	Various charge rates and temperature profiles
13	Lifetime Discharge	Executing CDC x5 under nominal charge/discharge rates
14	Inspection	Post-Thermal #2 and Lifetime Discharge
15	Pulse	High current pulses to evaluate voltage drop
16	Short Circuit	
17	Inspection	Post-Short Circuit
18	CDC	Post-Short Circuit CDC
19	30-Day Retention	

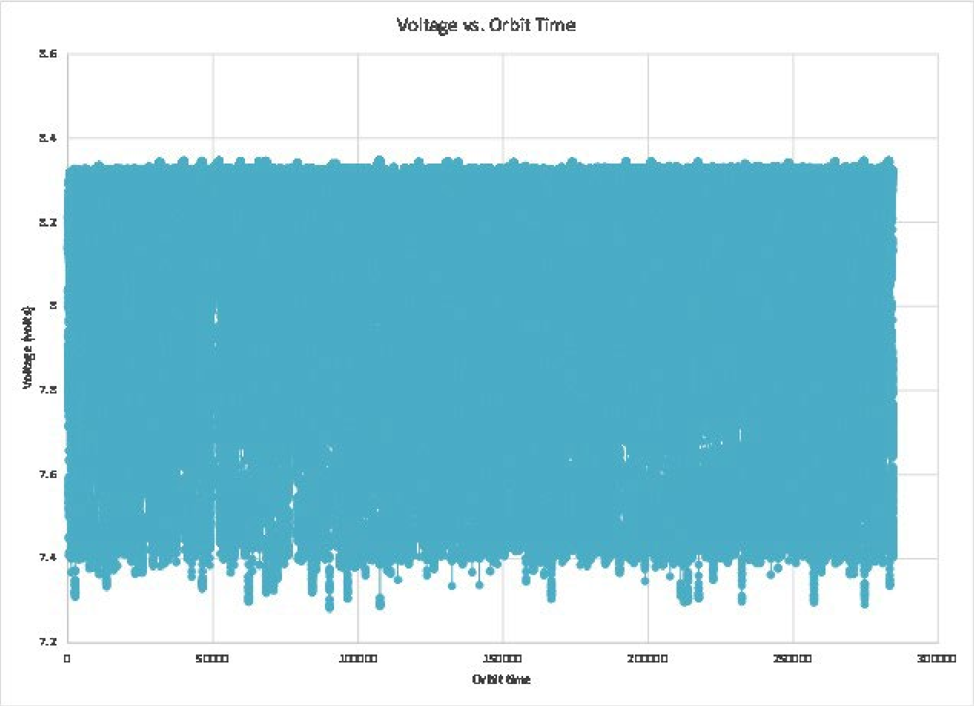
20% DoD Cycling Data Summary

- Nominal 20% DoD testing started on August 11, 2021 and concluded on September 25, 2021
  - 200 Cycles completed with no noticeable capacity fade
  - ~ 6,800 Coulombs planned removed from the battery equaling 20% of the energy (1.889 Ah)
    - ~1,700 Coulombs removed per parallel string (0.472Ah)



Time

Voltage



Time

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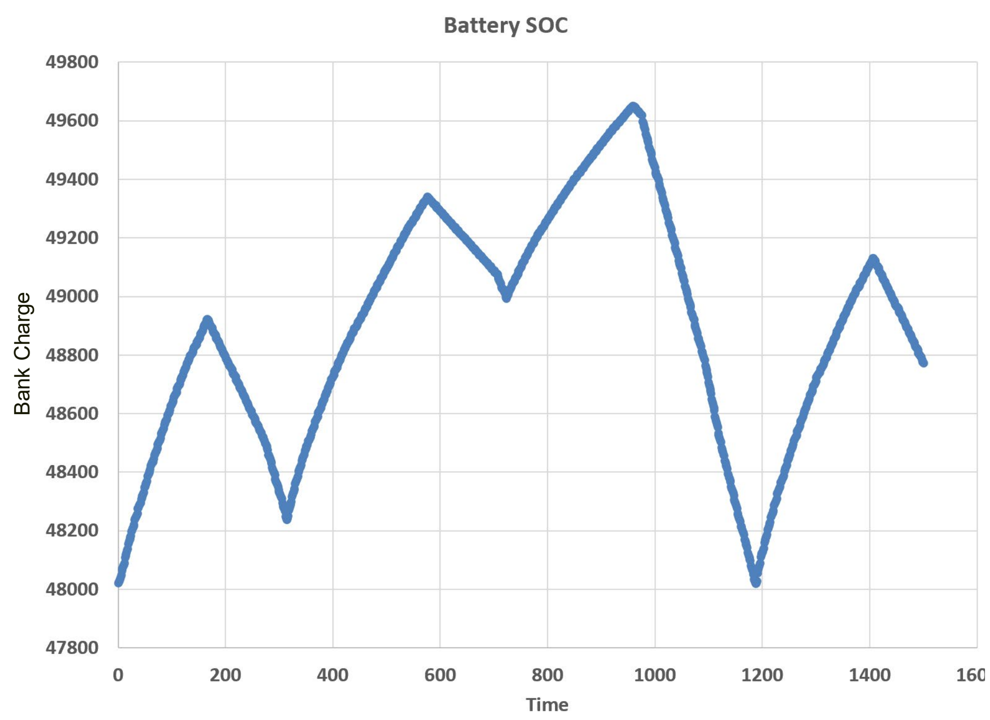
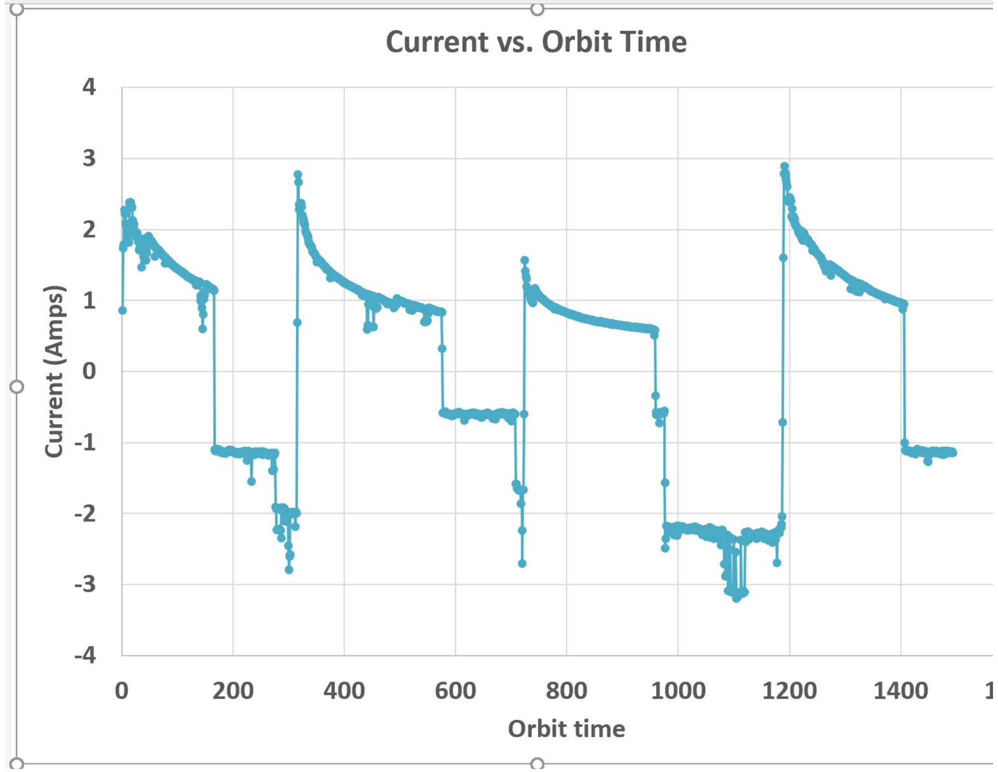
20% DoD Cycling Data Summary

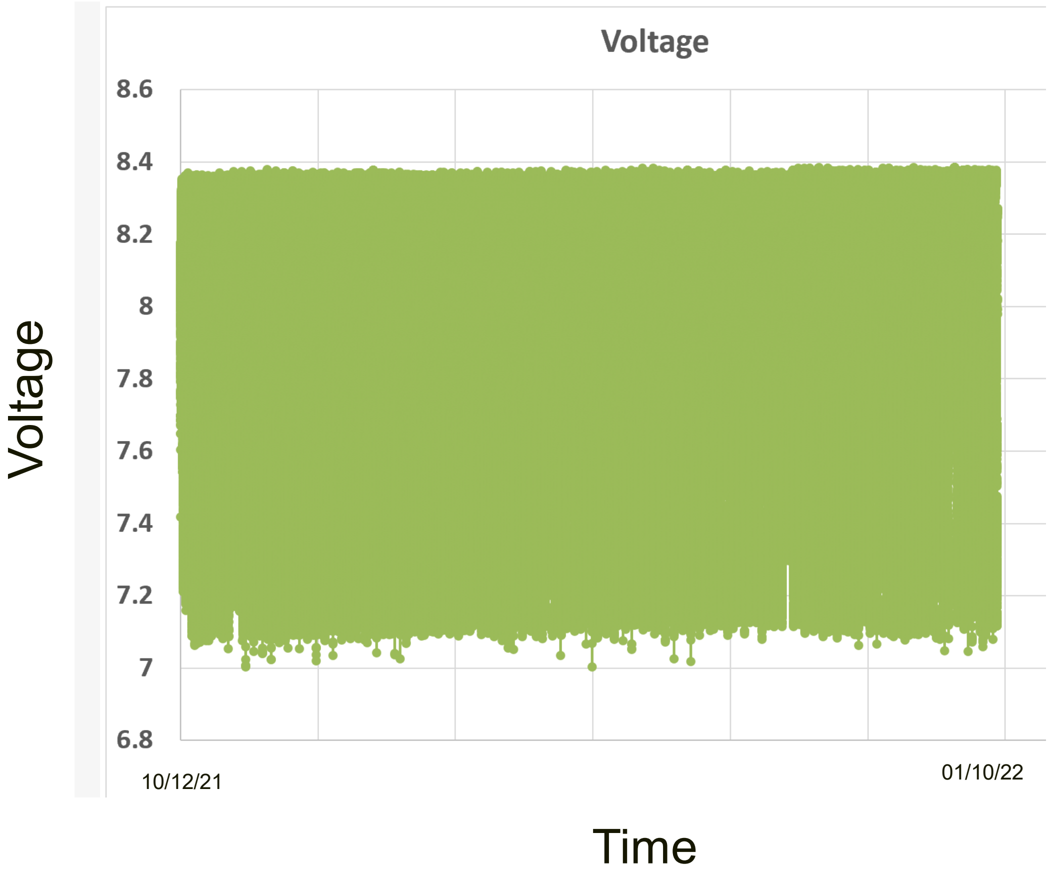
- Due to orbital parameters and the ability of the solar arrays to provide charge power, it takes several orbits to fully charge the battery





40% DoD Cycling Data Summary

- Nominal 40% DoD testing started on October 12, 2021 and concluded on January 10, 2022
  - 200 Cycles completed with no noticeable capacity fade
  - Again, took multiple orbits to fully recharge the battery prior to the next 40% Discharge
  - ~ 13,392 00 Coulombs planned removed from the battery equaling 40% of the energy
    - ~3,150 Coulombs removed per parallel string which was a bit lower than the planned 3,348 Coulombs per string



EnerSys / NASA JPL Projects

- EnerSys and NASA JPL teamed up to develop high energy, wide operation temperature chemistries
  - Delivering high energy between -40° to +60°
  - Long cycle life (>500 cycles @ 100% DoD)
  - Can be produced in 18650 or prismatic mechanical formats
  - Examining performance of foreign & domestic anode and cathode materials
    - Domestic EnerSys Graphite anode and Lithium Nickel Cobalt Aluminum Oxide (NCA) cathode produced by EnerSys under a USG Title III program
    - Domestic Graphite and Forge Nano Foreign Lithium Nickel Manganese Cobalt Oxide (NMC)
      - Forge Nano ALD coated MCMB Graphite and NMC-811

EnerSys / NASA JPL Projects

- QRD Series Cells: **ALD Coated Graphite – ALD Coated $LiNi_{0.80}Co_{0.20}Mn_{0.20}O_2$ (NMC 811) Cells (1.80 Ah Nameplate)**
  - 4 Different electrolyte variants studied.
  - Tests completed:
    - Initial Characterization at +20°C (C/5 rates, 2.50V to 4.10V)
    - Initial Characterization at 0°C (C/5 rates, 2.50V to 4.10V)
    - Initial Characterization at -20°C (C/5 rates, 2.50V to 4.10V)
    - Discharge rate characterization testing with room temperature charging (in order performed)
      - Discharge testing at -40°C: C/50, C/20, C/10, C/5, C/2, 1.0C, 1.5C
      - Discharge testing at -50°C: C/50, C/20, C/10, C/5, C/2, 1.0C
      - Discharge testing at -60°C: C/50, C/20, C/10
      - Discharge testing at -30°C: C/50, C/20, C/10, C/5, C/2, 1.0C, 1.5C
      - Discharge testing at -20°C: C/50, C/20, C/10, C/5, C/2, 1.0C, 1.5C
      - Discharge testing at +60°C: 1.5C
    - Cycle life testing at +25°C, 100% DOD, C/5 rates, 2.50V to 4.10V: *Testing on going*

EnerSys / NASA JPL Projects

Graphite - NMC 811 Cells (1.80 Ah Nameplate)

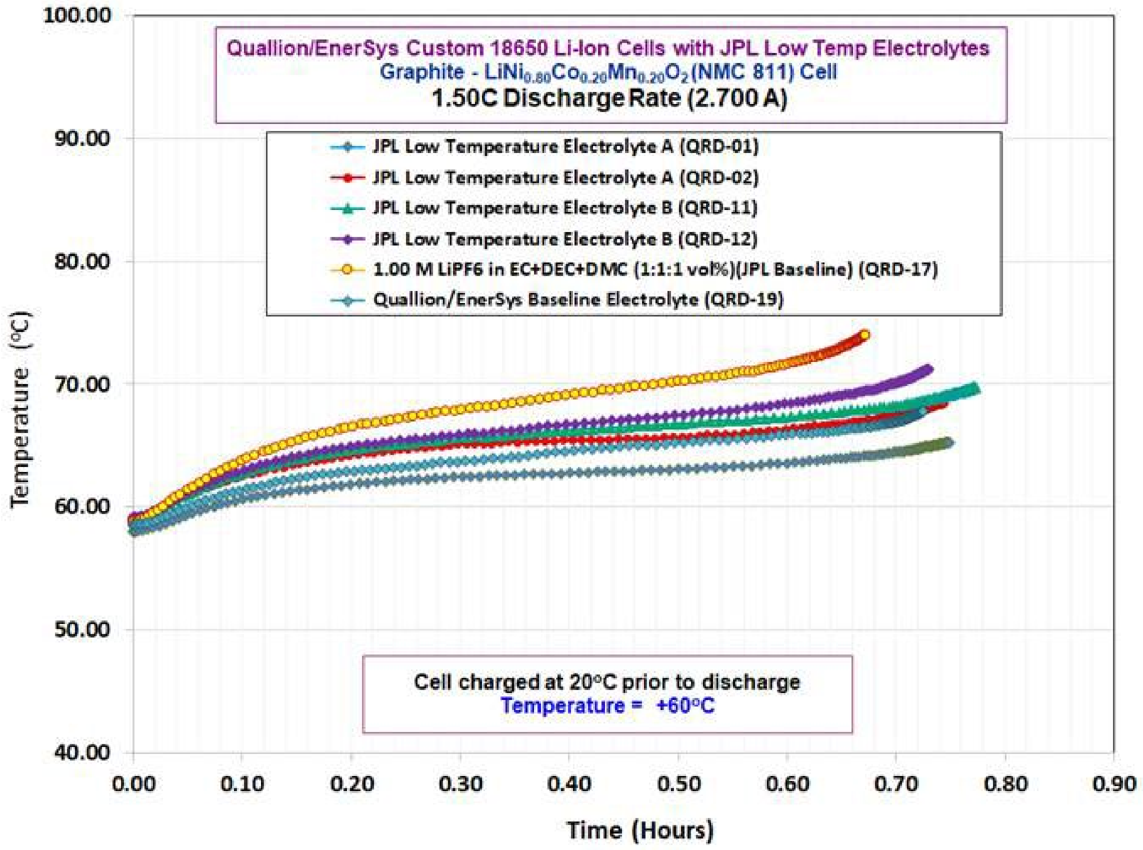
- JPL Electrolyte formulation B provided the highest available energy delivery at the lowest temperature and at the highest discharge rates.
- Electrolyte and cell chemistry is not optimized for charge/discharge rates
- Cell Performance has not been characterized for cycle life assuming low temperature discharge / room temperature charge.

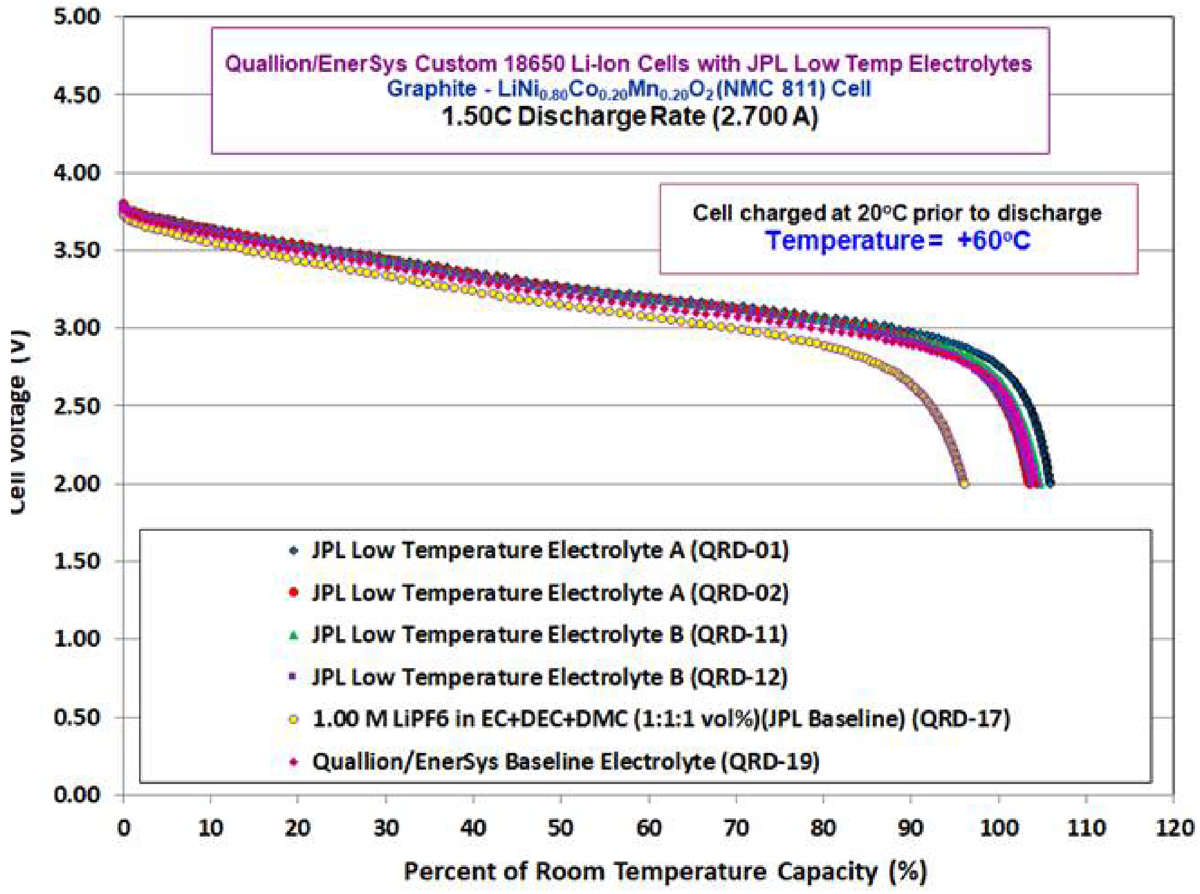
JPL Low Temperature Electrolyte B

Temperature (°C)	Rate	Current (mA)	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp
+ 60°C	1.5C	2700	1.9704	6.3514	166.86	103.87
20°C	C/5	50	1.8970	6.9036	181.37	100
- 20°C	1.5C	2700	1.3302	3.7843	99.42	70.12
	C/2	900	1.4389	4.7189	123.98	75.85
	C/5	360	1.5421	5.3652	140.96	81.29
- 30°C	1.5C	2700	1.2323	3.2597	85.64	64.96
	C/2	900	1.3263	4.1055	107.86	69.92
- 40°C	1.5C	2700	1.1407	2.829	74.32	60.13
	C/2	900	1.1516	3.2548	85.51	60.71
- 50°C	1.0 C	1800	0.4487	1.1089	29.13	23.65
	C/2	900	0.7303	1.9071	50.10	38.50
	C/5	360	1.1350	3.1038	81.54	59.83
- 60°C	C/10	180	0.9107	2.2455	59.00	48.00
	C/20	90.0	1.1094	2.8864	75.83	58.48
	C/50	36.0	1.2535	3.5892	94.30	66.08

+60°C Testing Details

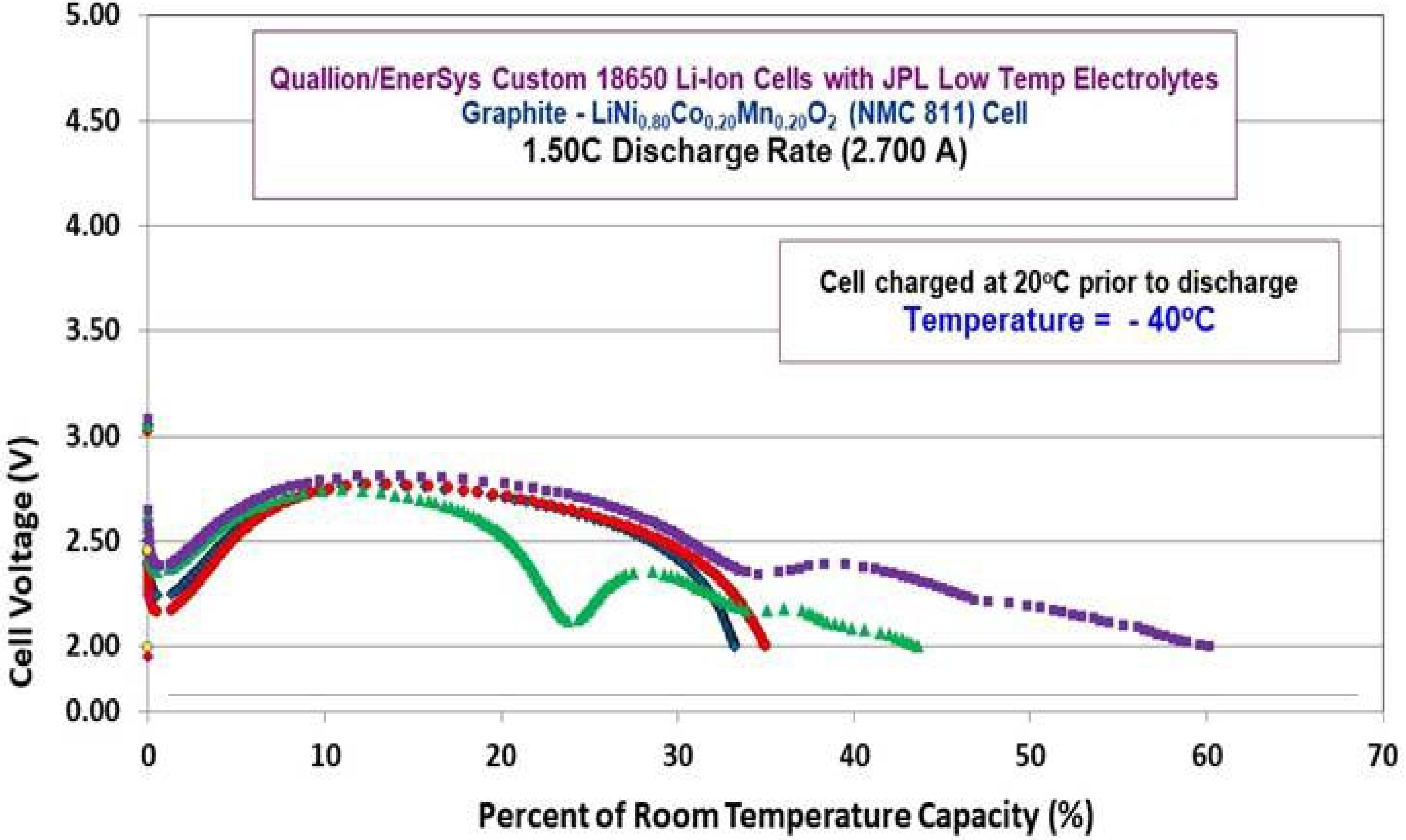
Graphite - NMC 811 Cells (1.80 Ah Nameplate)





-40°C Testing Details

Graphite - NMC 811 Cells (1.80 Ah Nameplate)



EnerSys / NASA JPL Projects

- **QSC** Series Cells: **Graphite/15% SiO - $LiNi_{0.80}Co_{0.15}Al_{0.05}O_2$ (NCA) Cells (2.40 Ah Nameplate)**
  - 6 Different electrolyte variants studied.
  - Tests completed:
    - Initial Characterization at +25°C (C/10 charge and C/5 discharge, 2.50V to 4.10V)
    - Initial Characterization at 0°C (C/10 charge and C/5 discharge, 2.50V to 4.10V)
    - Initial Characterization at -20°C ((C/10 charge and C/5 discharge, 2.50V to 4.10V)
    - Discharge rate characterization testing with room temperature charging (in order performed)
      - Discharge testing at -40°C: C/50, C/20, C/10, C/5, C/2, 1.0C, 1.5C
      - Discharge testing at -50°C: C/50, C/20, C/10, C/5, C/2, 1.0C
      - Discharge testing at -60°C: C/50, C/20, C/10, C/5, C/2, 1.0C

EnerSys / NASA JPL Projects

Graphite/15% Silicon - NCA Cells (2.40 Ah Nameplate)

			QCS-04				QCS-09				QCS-24			
			JPL Wide Temperature Range Electrolyte A				JPL Wide Temperature Range Electrolyte C				JPL Low Temperature Electrolyte B			
Temperature (°C)	Rate	Current (mA)	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp
25°C	C/5	480	2.2089	7.967	173.98	100	2.2297	8.045	175.35	100	2.1410	7.770	168.52	100
- 40°C	1.0 C	2200	1.6692	4.3302	94.57	75.56	1.7314	4.5238	98.59	77.65	1.4232	3.6187	78.48	66.47
	C/2	1100	1.5931	4.2464	92.74	72.12	1.7483	4.7015	102.47	78.41	1.5143	3.9764	86.24	70.73
	C/5	440	1.7806	5.1490	112.45	80.61	1.9177	5.6109	122.29	86.01	1.7922	5.0759	110.08	83.71
	C/10	220	1.9119	5.9209	129.30	86.55	2.1686	6.8412	149.10	97.26	1.9329	5.9239	128.47	90.28
	C/20	110	2.0172	6.5602	143.27	91.32	2.0808	6.8345	148.95	93.32	2.0232	6.5982	143.10	94.50
	C/50	44	2.1083	7.2592	158.53	95.44	2.1369	7.4035	161.36	95.84	2.0044	6.9323	150.34	93.62

EnerSys
Power/Full Solutions

EnerSys / NASA JPL Projects

Graphite/15% Silicon - NCA Cells (2.40 Ah Nameplate)

				QCS-04 JPL Electrolyte A			
Test	Temperature (°C)	Rate	Current (mA)	Capacity (Ah)	Watt-Hours (Wh)	Energy (Wh/Kg)	% of Room Temp
A	25°C	C/5	480	2.2089	7.967	173.98	100
W	0°C	C/5	480	2.0438	7.303	159.48	92.52
V	- 20°C	C/5	480	2.0050	6.866	149.96	90.77
U	- 30°C	C/5	480	1.9420	6.265	136.82	87.91
J	- 40°C	1.5C	3300	1.6760	4.3256	94.47	75.88
H		1.0 C	2200	1.6692	4.3302	94.57	75.56
G		C/2	1100	1.5931	4.2464	92.74	72.12
P	- 50°C	1.0 C	1800	0.0071	0.0154	0.34	0.32
O		C/2	900	0.9787	2.4057	52.54	44.30
T	- 60°C	C/5	360	0.2753	0.5875	12.83	12.46
S		C/10	180	0.5608	1.3392	29.25	25.39
R		C/20	90.0	1.0346	2.6541	57.96	46.84
Q		C/50	36.0	1.6402	4.7251	103.19	74.25

QUALLION

Thank You!

- Special thanks to:
  - The team at Spire Global (Jeff Bryan, Jordan Smith, Jordan Bridgeman)
  - The team at EnerSys/Quallion (Ryo Tamaki, Cesar Diaz and his team)
  - The team at Forge Nano (Paul Lichty, Daniel Higgs)
  - The team at Pyrotek (Bruce Gallaher, Michael Sekedat)
  - NASA JPL - Marshall Smart