AMERICAN LITHIUM ENERGY

STUDIES ON ZERO-VOLTAGE STABILITY OF ALE 4 AH 18650 CYLINDRICAL CELLS FOR NASA APPLICATIONS

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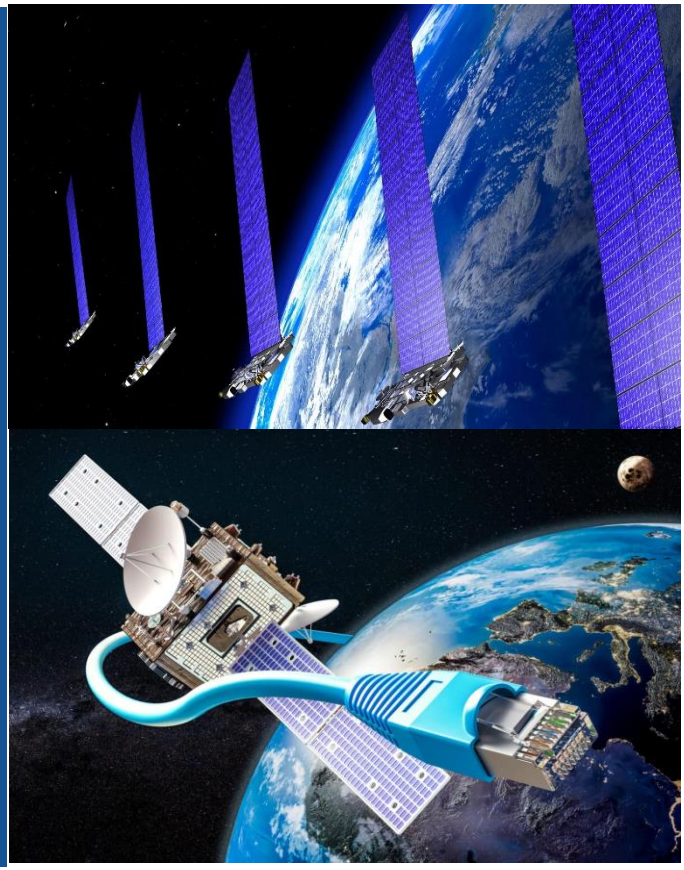

ALE Introduction

ALE's headquarters in Carlsbad, CA

- Founded in 2006 to develop advanced lithium-ion ("Li-ion") batteries initially for Department of Defense ("DoD") applications
- Full-time operational facility (24000 sq ft) for battery R&D, testing and production in San Diego County.
- Certification of **AS 9100D** quality system
- Innovative products for **DOD and medical applications**
- 13.2 million grants from California Energy Commission to scale up our 4Ah 18650 cell to 1.5 million cells per year and nano Si prismatic cells to >100K cells per year
- 50+ awarded US patents and 3 international patents

Advanced Silicon Anode Lithium Batteries for Defense, Aerospace, Medical, and EV Markets

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Defense Customers for USA-made Batteries

Outside USA-made batteries identified as strategic risk - long-term effort initiated to source onshore suppliers

NORTHROP GRUMMAN · Raytheon · inVENTUS POWER · L3HARRIS · Bren-Tronics, Inc. · NASA JPL

Unmanned Autonomous Systems	Space and Missiles	Advanced Energy Weapons & Vertical Lift Aircraft	Mini-Grid / Energy Storage	Wearables	Vehicles
EnergyCore Battery Technology	Missile/Missile Launch and Satellite Battery	Li-ion Battery/Supercap Hybrid Cell (LBSCHC)	Ultra-Lightweight Expeditionary Power System (U-LEPS)	Conformal Wearable Battery / SAPI Battery	6T Vehicle Battery Pack and BB-2590 Man-Portable Battery Pack using Non-Flammable High-Capacity Li-ion Cells

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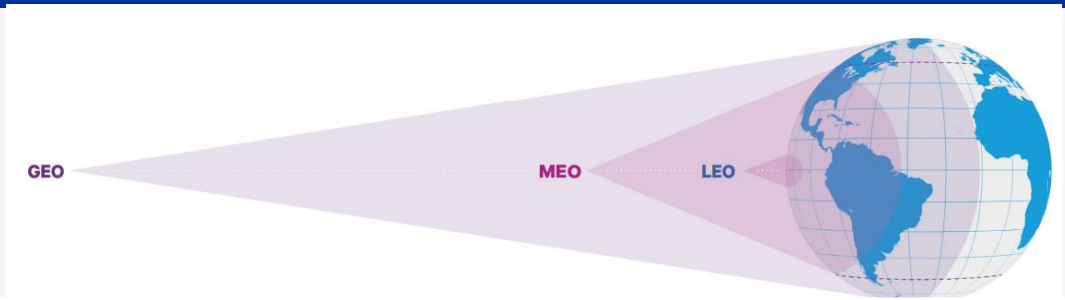
Challenge 1: Space Battery Requirements for Satellites



Satellite Orbit	GEO (Geostationary Earth Orbit)	MEO (Medium Earth Orbit)	LEO (Low Earth Orbit)
Altitude	36,000Km	5,000-20,000Km	500~1,200Km
latency	>500ms	<80ms	<30ms
Earth coverage	Very large	Large	Small
Satellites Required	Three	Six to Twenty	Hundreds to thousands
Time circle earth	24hr	2~12hrs	~90 minutes
Satellites Lifespan	~15 years	~10 years	5-7 years
Application	weather data, broadcast TV, and low-speed data communication	GPS, other navigation applications, and high-bandwidth data service	Real time data service, International Space Station, Star link for global coverage
Battery requirement	Long cycle life; long time storage; high energy density		

ALE batteries can meet these requirements

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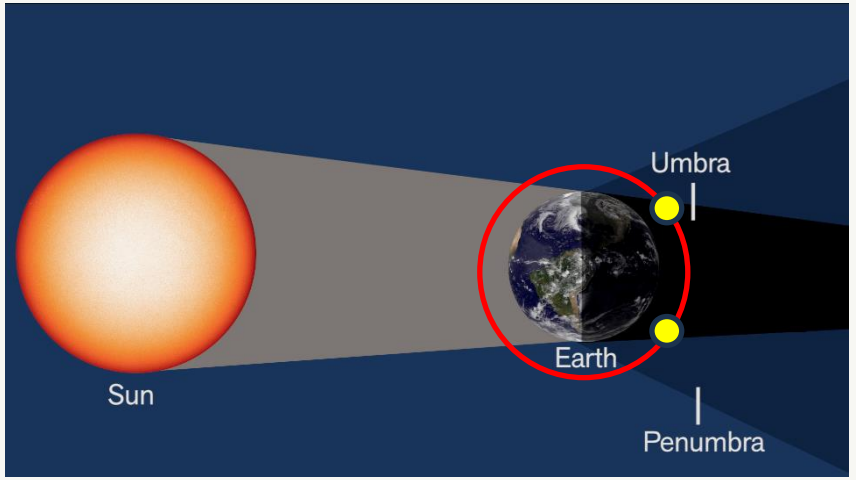
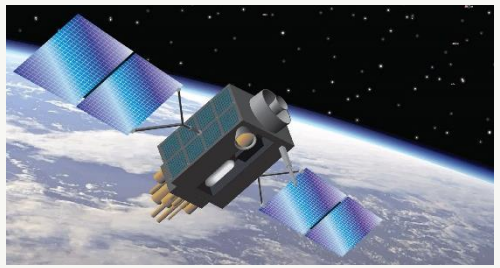
https://www.oceanweb.com/a-guide-geo-leo-and-meo-satellites/
https://www.starlink.com/business/maritime

Challenge 1: Space Battery Requirements for Satellites

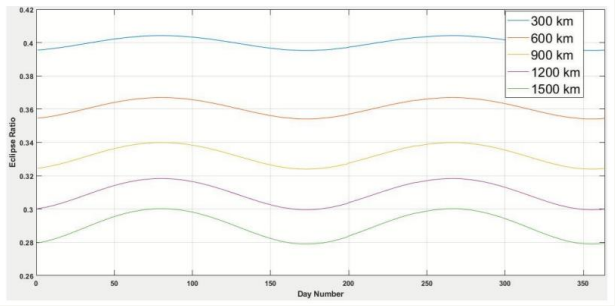
40,000 LEO satellites for Star link

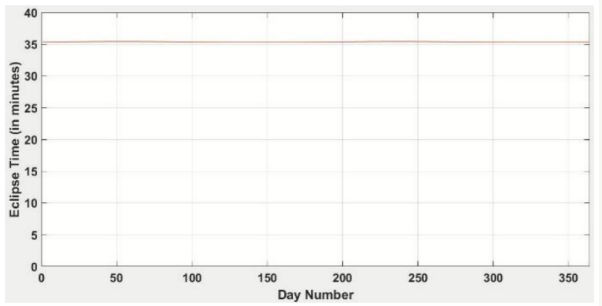


Satellite Eclipse



Mission	Satellite	Cycles	DOD (%)	Time (years)
1	LEO	15,000	20	3
2	LEO	25,000	20	5
3	LEO	75,000	20	15





Space battery needs for (1) matching lifespan of satellites
(2) matching numerous satellites for global coverage

~5000 times eclipse/year, 35 minutes/time

ALE's 4Ah 18650 cell can meet the cycle life requirement per two year's cycle life data

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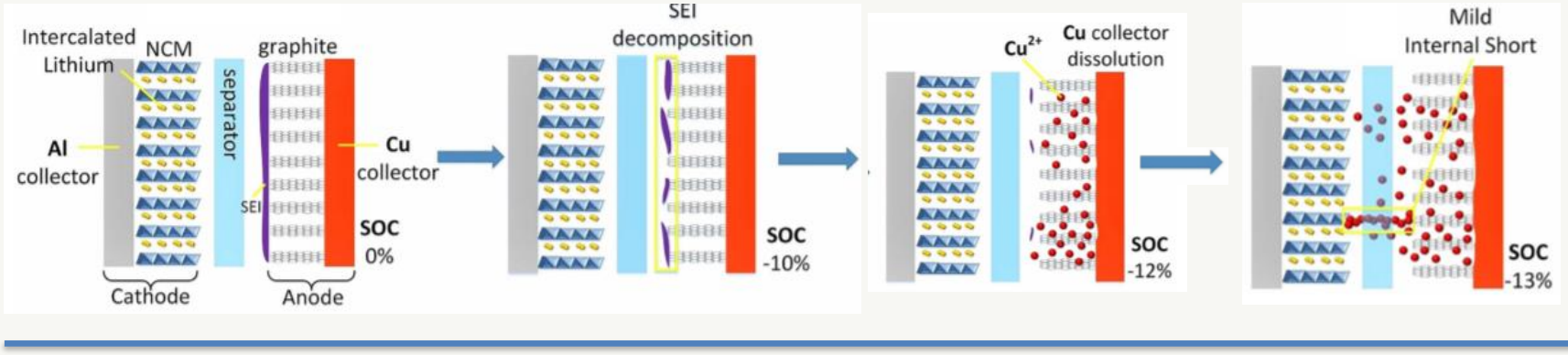
https://www.universetoday.com/156383/starlink-satellites-are-still-bright/

https://doi.org/10.15394/ijaaa.2019.1412 Computation of Eclipse Time for Low-Earth Orbiting Small Satellites. International Journal of Aviation, Aeronautics, and Aerospace, 6(5).

Challenge 2: Dead Bus Recovery – Zero Volt Stability

Battery Complete Discharge → Battery Failure → Spacecraft Power failure → Dead Bus

↓ Battery failure mode



Overdischarge Process: Cu dissolution and dendrites, Internal short

↑ Recovery Battery from Deep Discharge even Zero voltage Exposure

ALE Solutions: Prevent Cu dissolution at low Voltage

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Zero Voltage Technology

Challenge: When U is close 0 voltage, the potential of negative electrode increase to 3.56 V vs Li+/Li, the corrosion of negative (Cu foil) happen (Cu oxidization to Cu+)

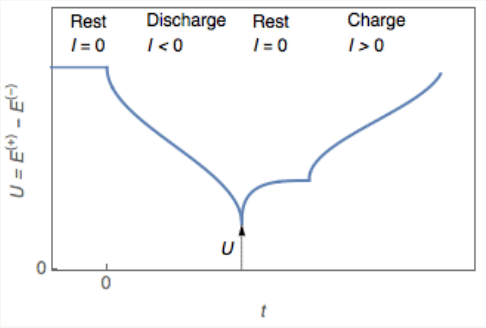
Negative Impact:

- Existing Li-ion batteries are dead or damaged if discharged to zero volt
- Billion dollars of satellite lost every year due to the dead bus caused by the failure of the batteries
- To avoid the dead bus issue, some low energy density batteries such as Ni-metal Hydride batteries (50 to 75 Wh/kg) were used for space application

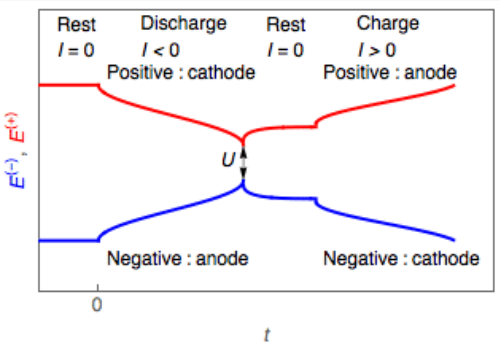
Solution: When a sacrificial electrode applied, whose corrosion happen first and protect Cu foil.

ALE Patented ZVT:

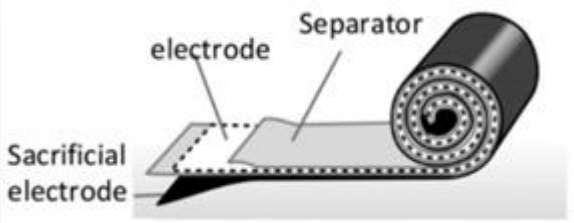
- Materials is low cost and not moisture sensitive or air sensitive
- Not participate in the normal electrochemical reaction
- The protection starts when the cell is assembled (close to zero voltage)
- Improved cycle life due to the protection in the wetting period before the formation
- Applicable to any lithium-ion battery cells when Cu foil is the current collector
- Very useful in the battery logistics, battery shelf life, and battery safety



Battery voltage



Potential of Negative and Positive electrodes



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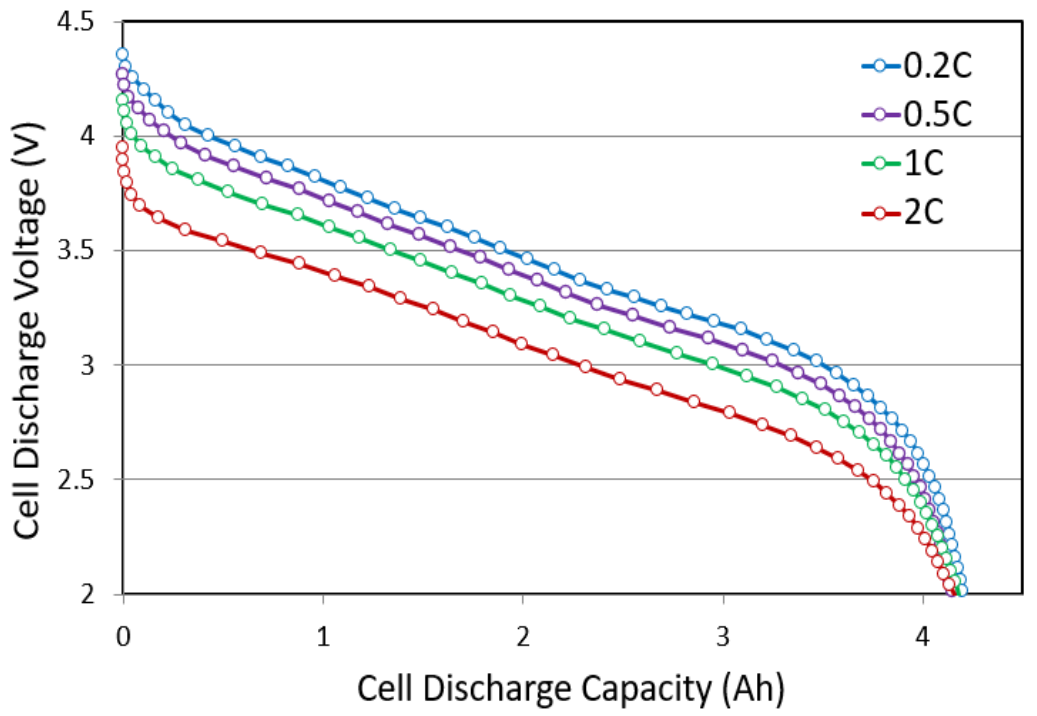
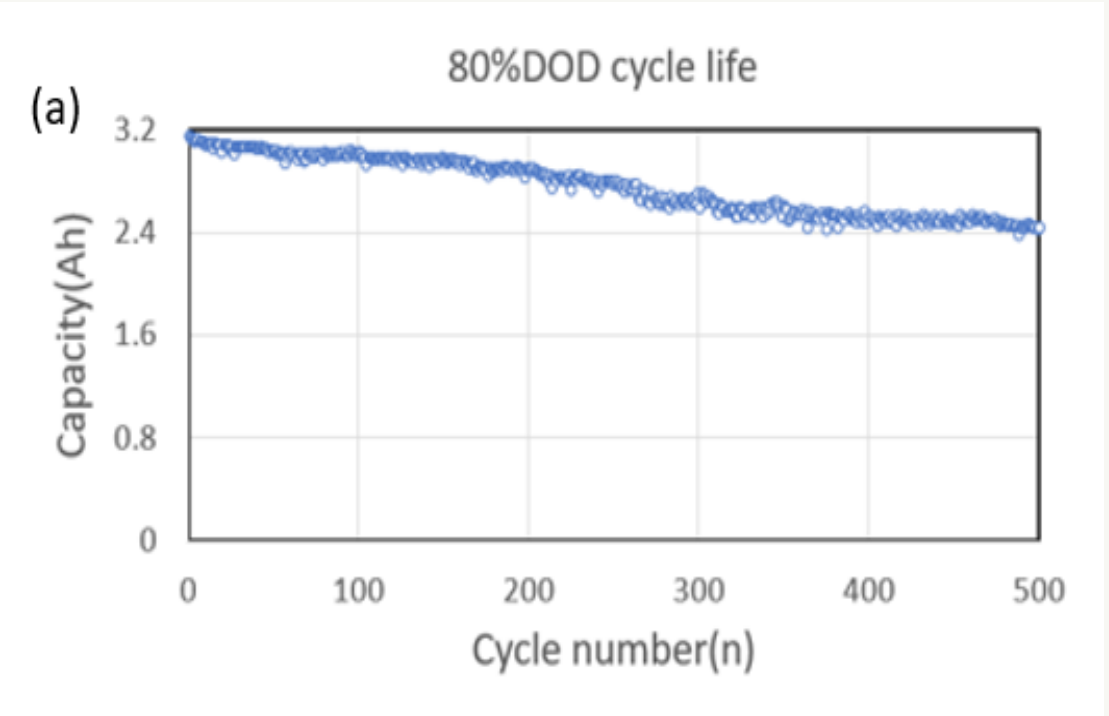
18650 Cell Performance at Room Temperature





- Cell capacity: 4.2Ah at different rates
- Specific energy:~330Wh/kg
- Specific power: ~700W/kg
- Cycle life: ~500 cycles at 80%DOD(80% retention)

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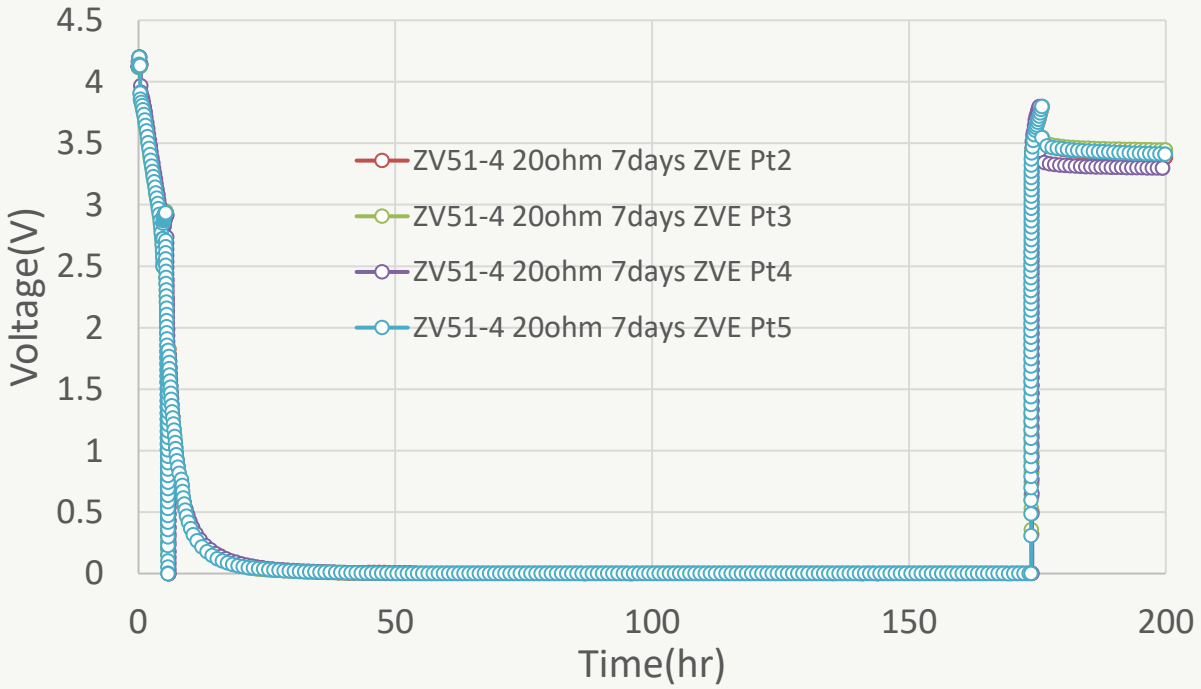
Zero voltage Exposure: Sacrificial Design with long life 1000 cycles



ZVE/20 ohm 7days	Capacity (4.2-2.5V)	Capacity (2.5-0V)	Capacity (0V 7days)
Pt1	3.199	0.366	0.310
Pt2	3.154	0.323	0.307
Pt3	3.120	0.330	0.299
Pt4	3.193	0.311	0.311
Pt5	3.136	0.321	0.300

- The cell capacity (4.2-2.5V) have little change after ZVE, the cell retention is 98% after ZVE 35 days (7days X5).

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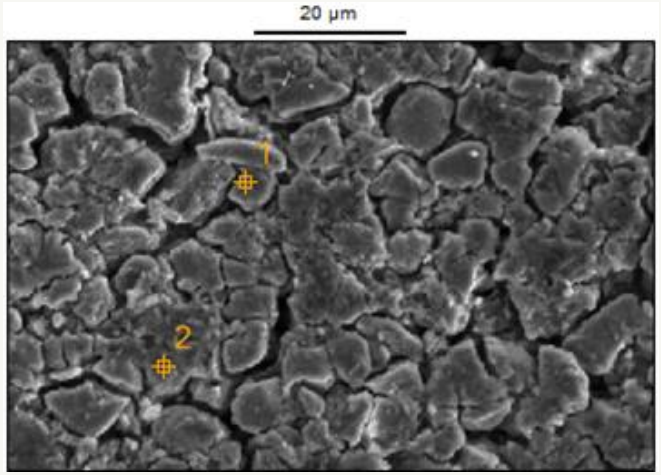
Microscopy: Non-Sacrificial Design

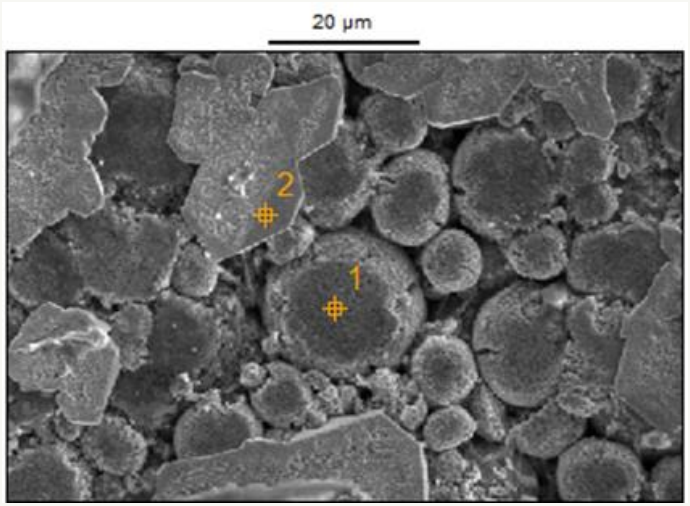
Negative Electrode



C-K	O-K	F-K	Na-K	Si-K	P-K	Cu-L
11.8	50.2	3.6	0.2	34.2		
35.1	35.4	8.3	0.5	19.2	0.9	0.6

Si/C anode confirmed
Cu foil severely corroded

Positive Electrode



C-K	O-K	Al-K	Mn-K	Co-L	Ni-L	Cu-L
16.7	52.9		2.1	2.3	25.9	
4.0	2.9	0.8		0.8	0.0	91.6

811 polycrystal sphere confirmed
Cu plate deposited on the positive electrode

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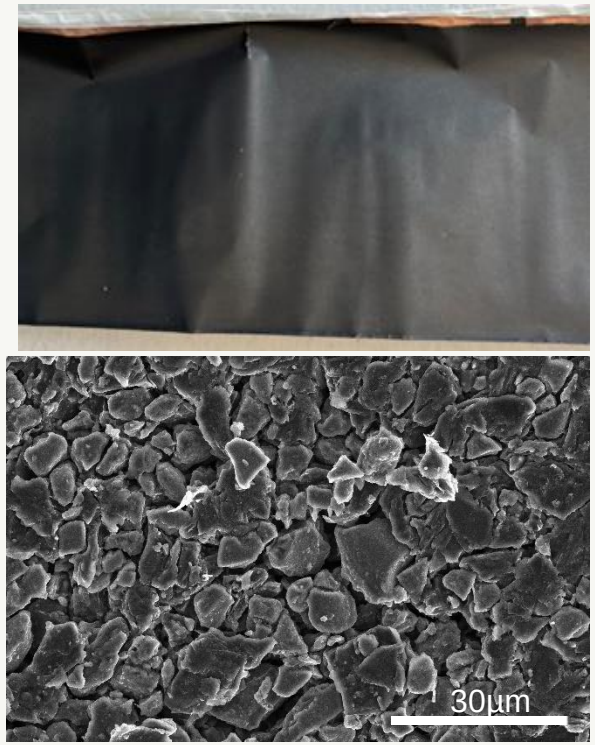
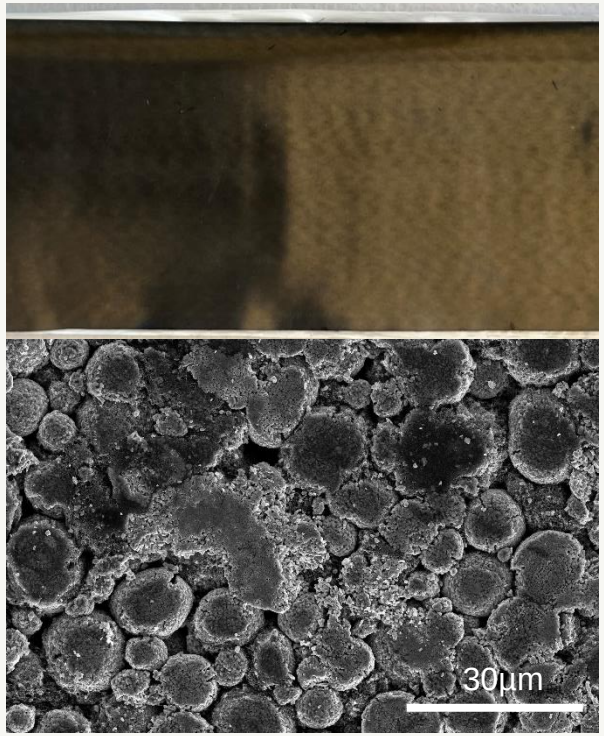
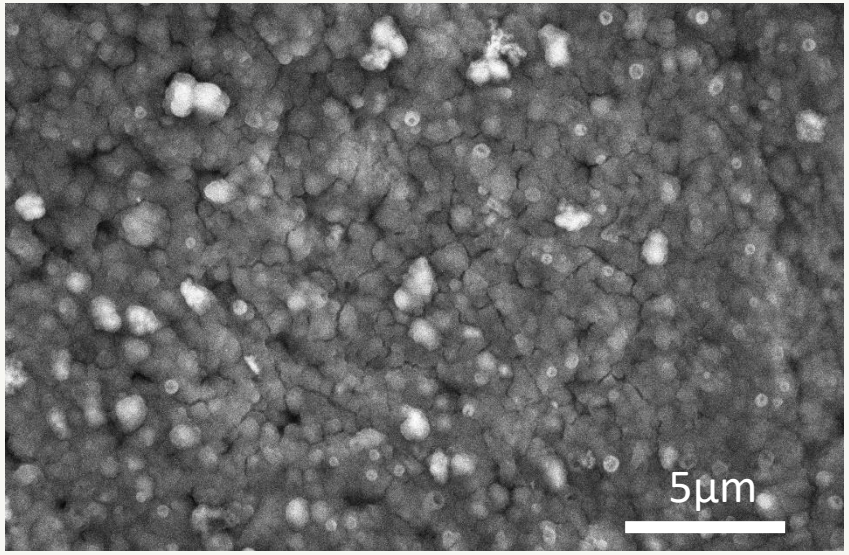
Microscopy: Sacrificial Design 2



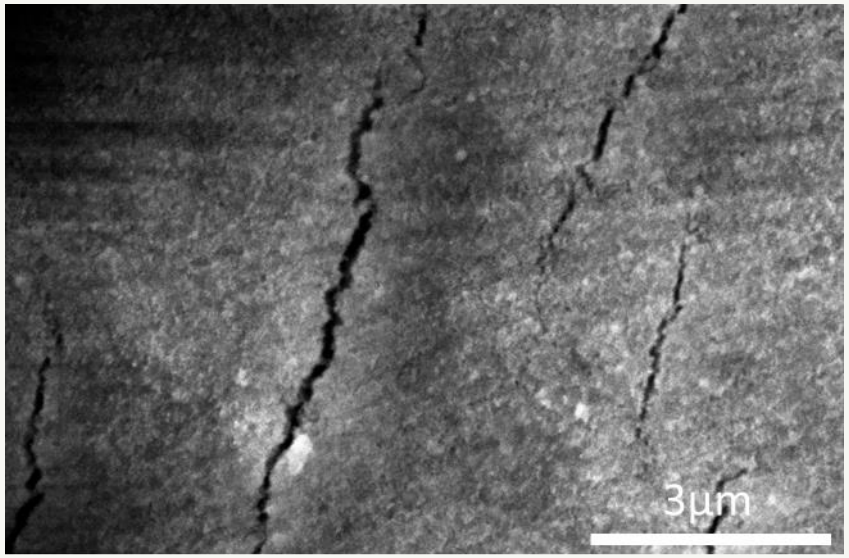
Negative Electrode
After ZVE 20ohm 7days X5



Positive Electrode
After ZVE 20ohm 7days X5



Sacrificial Electrode before ZVE



Sacrificial Electrode after ZVE

- No corrosion observed on negative and positive electrode
- Deep cracks observed from electrochemical sacrificial protection

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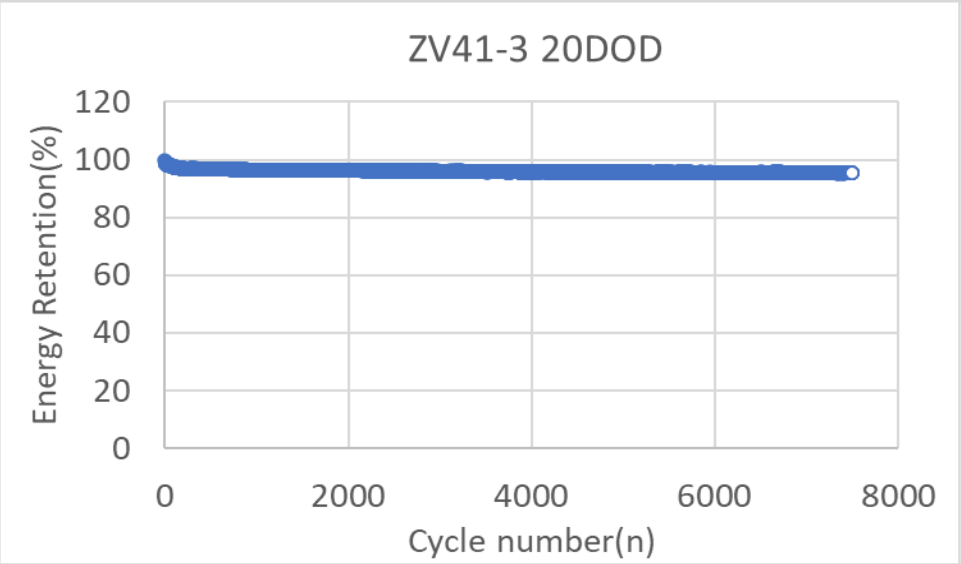
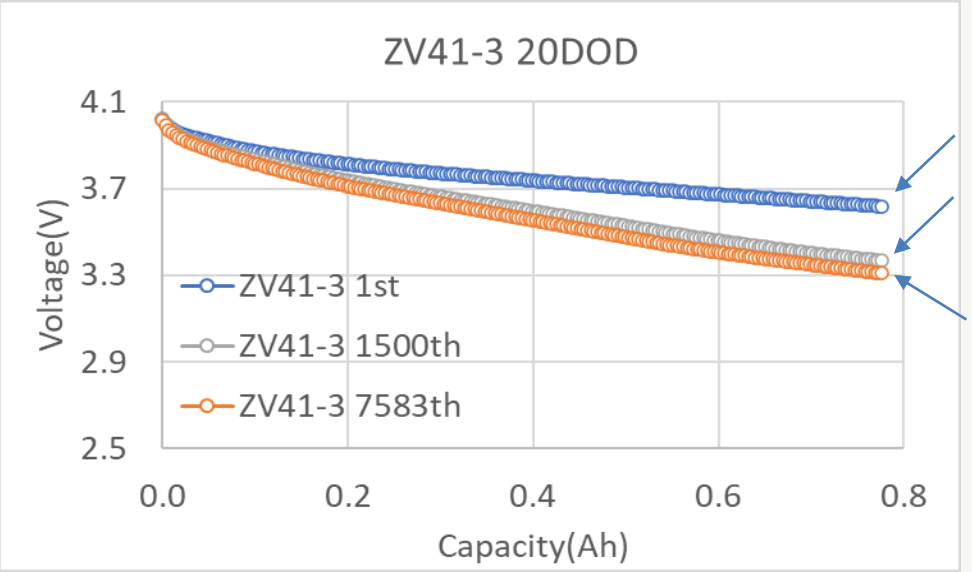
20%DOD: Sacrificial Design 1





3.67% loss
- **Polarization cumulation**
- **Decrease in SoC**
- **Cell degradation**

1% loss
- **Cell degradation**

Cycle number	1	1500	7583
End voltage	3.6176	3.3663	3.3094
Energy retention	100%	96.33	95.34

Test Procedure:
Discharge C/3: 35 minutes
Charge C/4.5 to 4.1V cut off C/20: 60minutes

- ~3.67% reversible discharge polarization energy reduction from 1st to 1500th cycle (equilibrium state to steady state)
- ~0.99% discharge loss from 1500th to 7583rd cycle.
- Projected cycle life: >94,255 cycles (18 years); larger than the 75,000 cycles (15 years).

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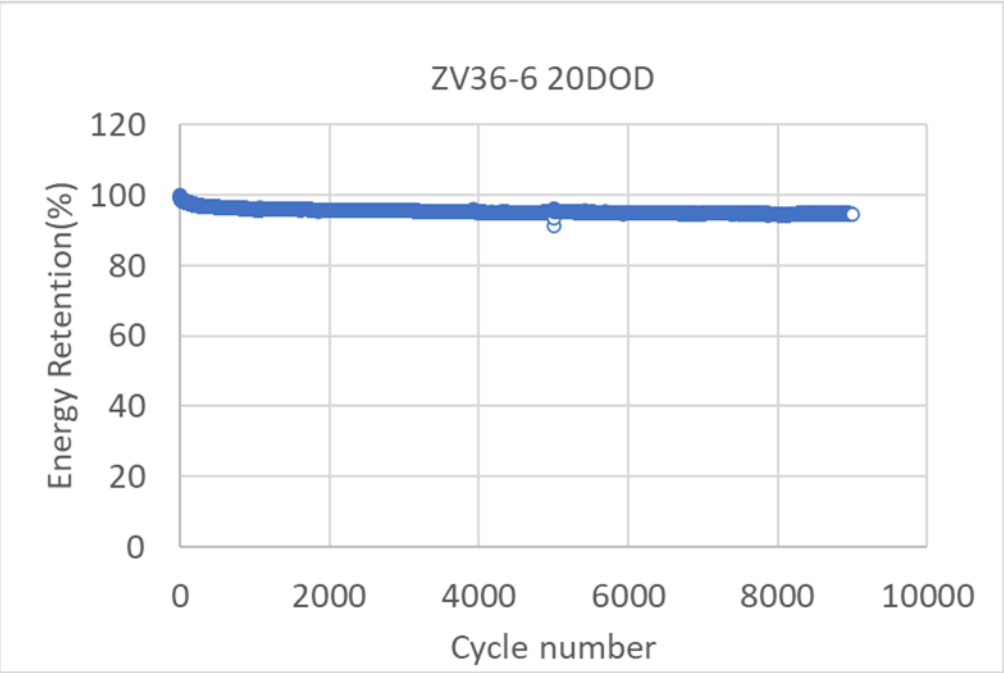
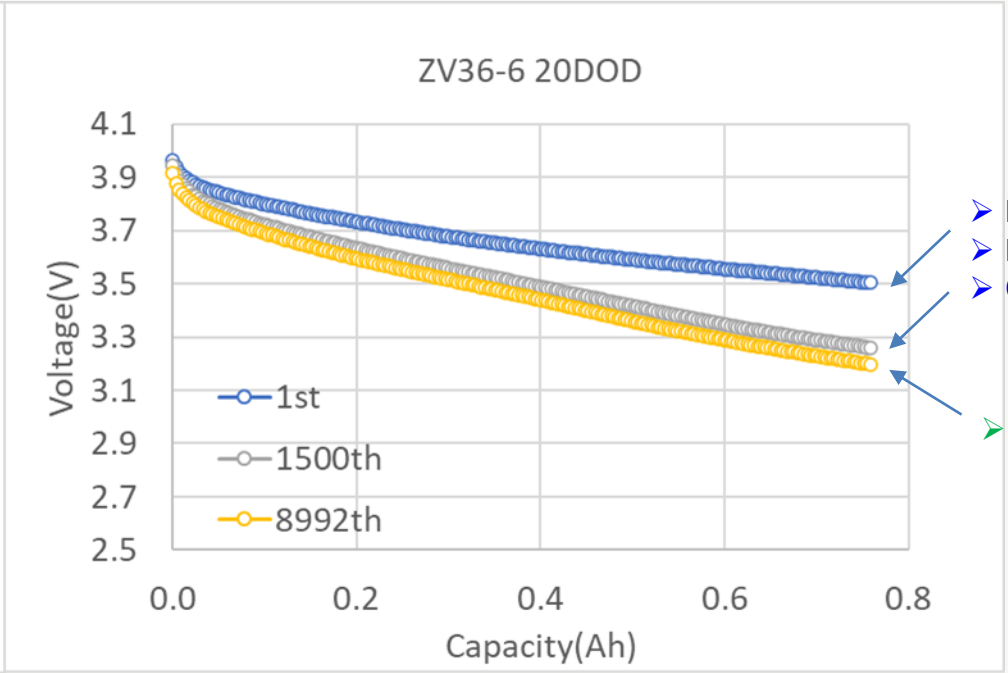
20%DOD: Sacrificial Design 2





3.96% loss
- **Polarization cumulation**
- **Decrease in SoC**
- **Cell degradation**

1.3% loss
- **Cell degradation**

Cycle number	1	1500	8992
End voltage	3.5038	3.2596	3.1978
Energy retention	100%	96.04	94.73

Test Procedure:
Discharge C/3: 35 minutes
Charge C/4.5 to 4.0V cut off C/20: 60minutes

- ~3.96% reversible discharge polarization energy reduction from 1st to 1500th cycle (equilibrium state to steady state)
- ~1.31% discharge loss from 1500th to 8992nd cycle.
- Projected cycle life: >85,838 cycles (17years); larger than the 75,000 cycles (15 years).

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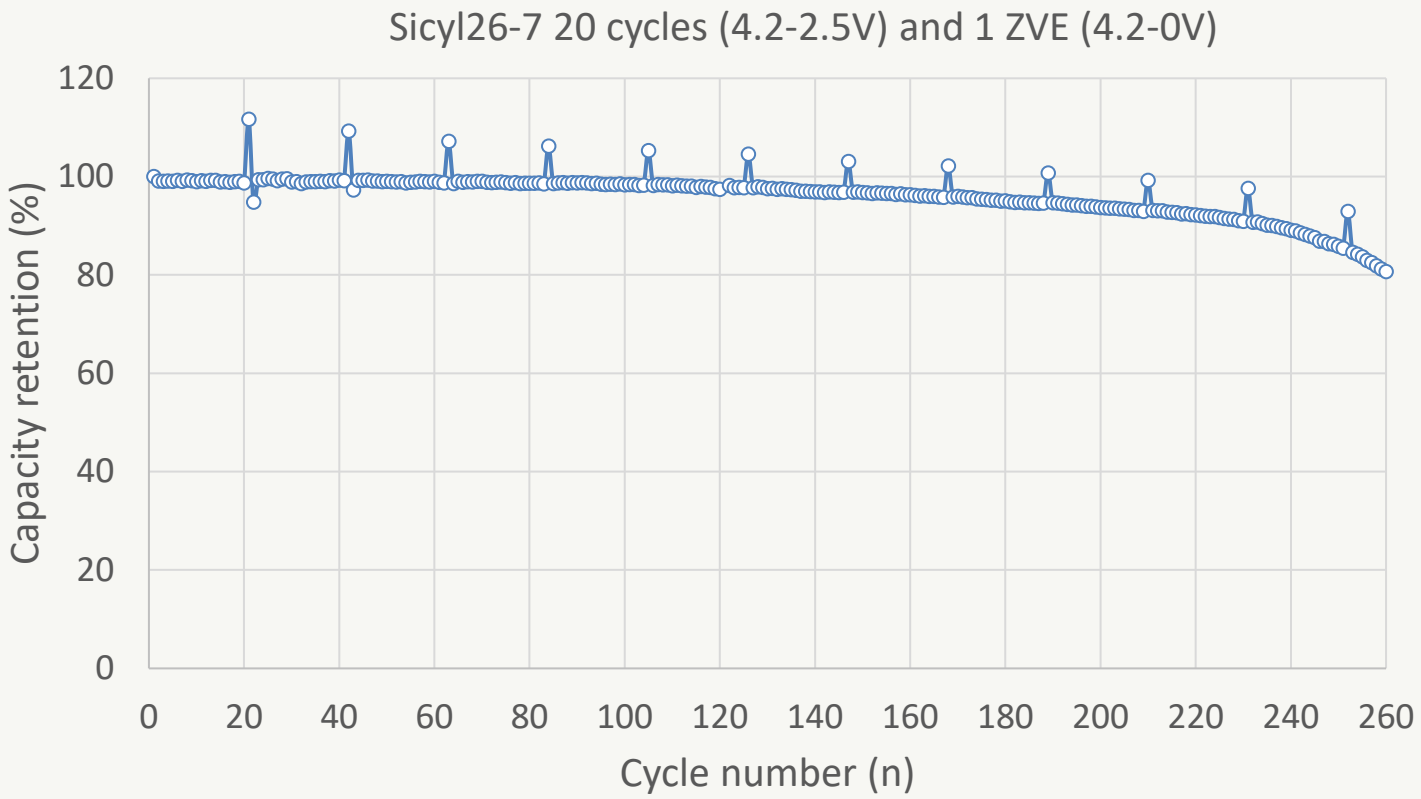
100%DOD: Sacrificial Design 3



Cycles	Capacity (4.2-2.5V)	Capacity (4.2-0V)
1st, 21st	3.755	4.193
22nd, 42nd	3.564	4.103
43rd, 63rd	3.654	4.025
64th, 84th,	3.702	3.987
85th, 105th	3.703	3.952
…	…	…
232nd, 252nd	3.407	3.488
260th	3.029	NA

- Cell are tested 20 cycle life (4.2-2.5V) and 1 cycle life (4.2-0V); and looped 12 times.
- 260 cycle life with 80% capacity retention. The major failure mode is due to the cell being over discharged repeatedly. The Cu dissolution should not be the cause of the capacity loss per cycle

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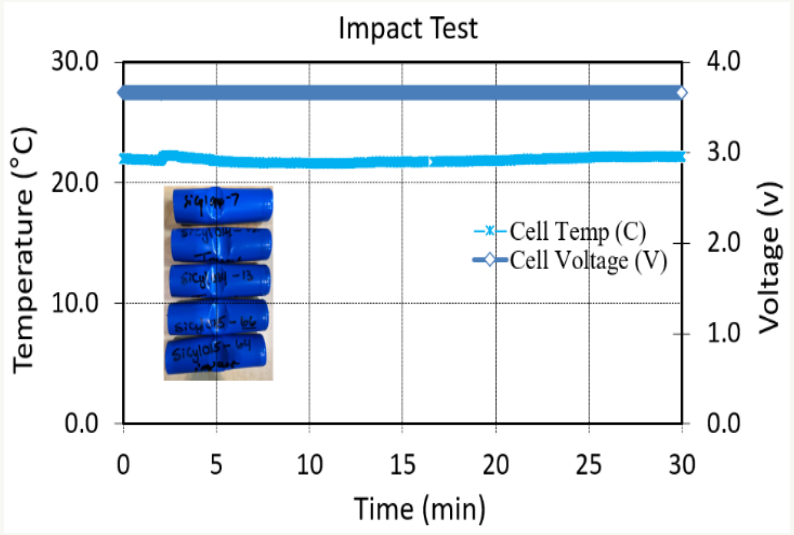
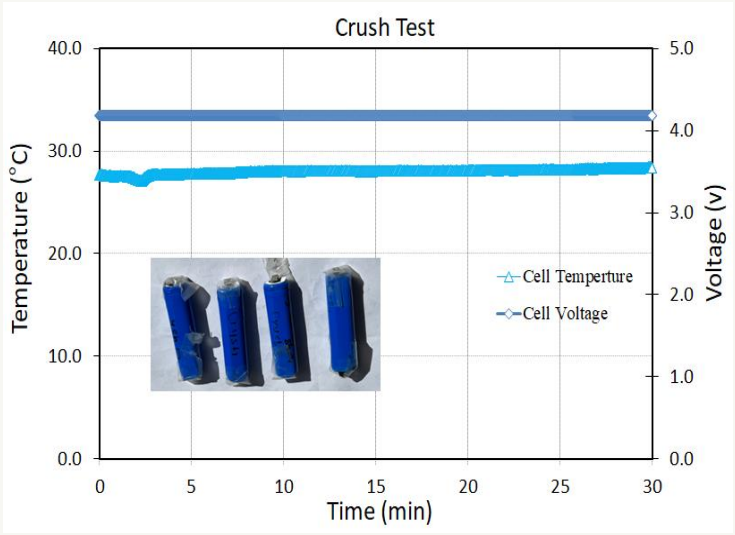
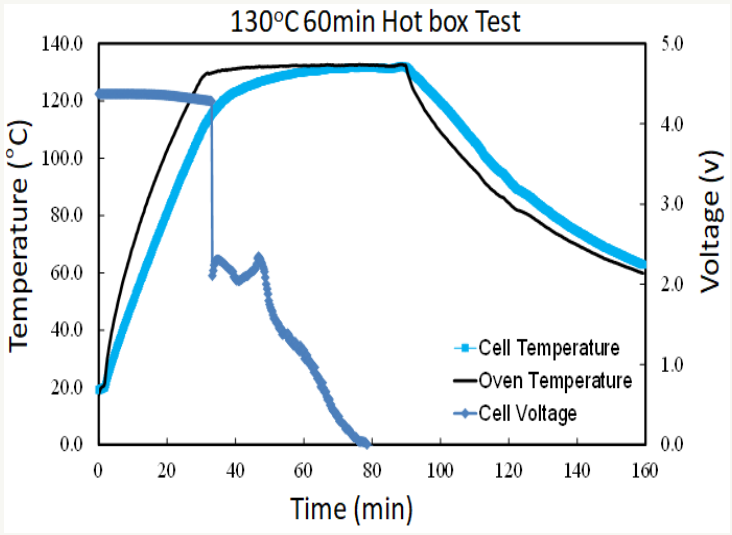
Safety







- 18650 4Ah passed Impact, Crush, and Hotbox test

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Summary

- 18650 4h cells have been designed and built with ~330Wh/kg and 700W/kg.
- 18650 4h cells have demonstrated excellent zero voltage stability, ~98% capacity retention after 20ohm 7days for 5 times. This is very promising for GEO and MEO satellites.
- The projected cycle life of 18650 4Ah ZVT cells should be >85,838 cycles (17years) per our two years cycle life data: ~1.3% energy loss from 1500th to 9000th after electrochemical stabilization.
- 18650 4Ah cells have passed impact, crush, and hotbox tests per UN standard.