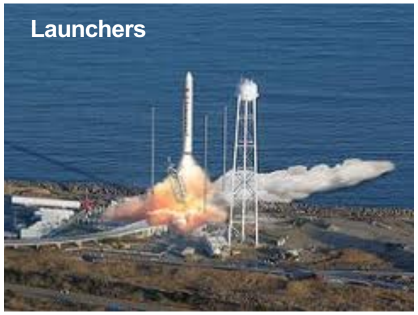
LEO Cycling Performance after Zero Volt Storage of 8 Series Test Module with EnerSys Lithium Ion Chemistry for the Aerospace Application



POWERED *by*

Hiroshi Nakahara, Ryo Tamaki, Blake Cardwell, Grant Farrell, Ben Scott, Kevin Schrantz

EnerSys Proprietary

Outline

1. **History of product development in EnerSys Advanced Systems (EAS) – ABSL – Quallion**

2. **Introduction of ZeroVolt technology (Cell level tests)**
   1. ZeroVolt chemistry design verification
   2. ZeroVolt cell characterization for aerospace application

3. **8 cell series module evaluation**
   1. 0V storage characterization for 4 months
   2. Module characterization during 20% DOD LEO cycling after 0V storage

EnerSys Advanced Systems

$100M Division Consisting of 6 Business Units

- **Space**
  - Launch Vehicles
  - Satellites
  - Manned
  - Interplanetary & Landers
- **Aviation**
  - Fixed Wing & Rotary Aircraft including F16/18 & 777
  - UAV's & Target Drones
- **Munitions**
  - Missiles & Smart Weapons
  - Guided Bombs & Projectiles
  - Electronic Fusing
- **Land**
  - Combat, Tactical & Unmanned Ground Vehicles
  - Microgrids & Forward Operating Bases
- **Sea**
  - Submarines
  - Unmanned Underwater Vehicles
- **Medical**
  - Cochlear Implant Speech Processors
  - Neromodulation
  - Pumps

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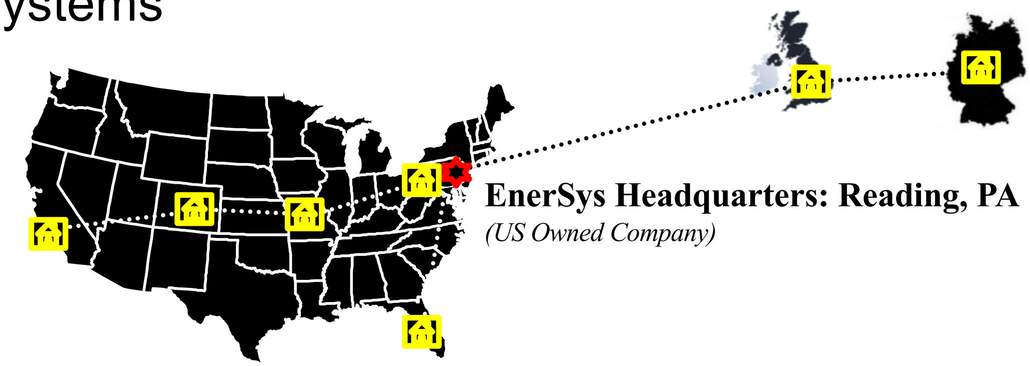
Facility Locations

EnerSys Advanced Systems

EAS Manufacturing Facilities

- Sylmar, CA
- Santa Clarita, CA
- Longmont, CO
- Warrensburg, MO
- Horsham, PA
- Tampa, FL
- Culham Oxfordshire, UK
- Newport, UK
- Zwickau, DE



Product Line	Brands	Technology	Main Manufacturing Locations
Space	ABSL/Quallion	Lithium-Ion Materials, Cells & Batteries	Longmont CO, Sylmar CA, Culham UK
Medical	Quallion	Lithium-ion Cells & Batteries	Sylmar CA
Munitions	EAS, Enser	Lithium Primary/Liquid Reserve	Horsham PA, Tampa FL
Land & Sea	Hawker/Armasafe	Lead Acid (Thin Plate), NiZn	Warrensburg MO, Zwickau DE
Aviation	Hawker/Quallion	Lead Acid (Thin Plate), Ni-Cd & Lithium-ion	Warrensburg MO, Sylmar CA, Newport UK, Zwickau DE

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EnerSys Power/Full Solutions

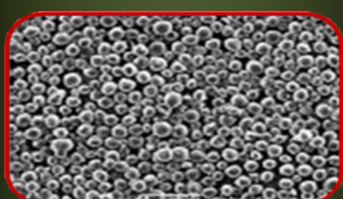
Overview of Battery Industry
Battery Market Stratification

ABSL QUALLION

Battery Market Stratification

Materials

Chemistries can be varied for high-energy, power, rate and capacity, safety.



Cell Design

Cell configurations include prismatic, cylindrical, flat stack, wound, large, small, polymer (pouch), hard case.

Electronics

Cell and battery management, power, safety, interface, communication (e.g., SM/CAN), balancing, state of health monitoring, modeling, grade of board parts.

Battery Pack

Pack design considerations: safety, interconnects, spacing of cells, thermal gradients, heat ejection, environmental requirements, interface to

EAS / Quallion is a full service provider with expertise at all stratifications of the battery market.

ABSL – Quallion – EnerSys Advanced Systems Aerospace Application

1998 — **Quallion** Established in California, USA

2000 — **ABSL** The 1st space flight battery manufacturer to qualify lithium-ion cells for space flight

2001 — **ABSL** The 1st lithium-ion battery to orbit earth (ESA's PROBA 1)

2003 — **Quallion** registered ISO 9001 &13485; Zero-Volt™ technology patented

2004 — **ABSL** The 1st lithium-ion battery to orbit Mars (ESA's Mars Express)

The 1st lithium-ion battery to power a comet probe (ESA's Rosetta)

2005 — **ABSL** The 1st lithium-ion battery to orbit Venus (ESA's Venus Express)

2006 — **ABSL** The 1st lithium-ion battery to power a NASA spacecraft (NASA's ST-5)

2007 — **Quallion** Title III Award; Registered AS9100

2009 — **ABSL** Powering NASA's return to the moon (NASA's LRO & LCROSS)

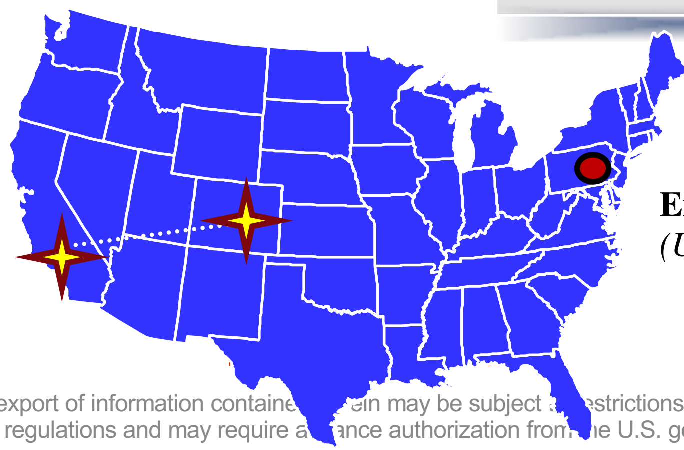
2011 — **ABSL** The first lithium-ion battery to provide power for astronaut life support (NASA's EMU)

2012 — **Quallion** 1st Satellite battery launched into orbit. Powers U.S. Military Satellite (TacSat 4)

2013 — **ABSL** 100th Lithium-ion battery launched

2014 — **EnerSys acquired Quallion.**

ABSL & **Quallion** combine space technologies



Los Angeles County, CA & Boulder County, CO

EnerSys Headquarters: Reading, PA
(US Owned Company)

Quallion – EnerSys Advanced Systems Medical Application

1998 — **Quallion** Established in California, USA

2003 — Commercial launch of Advanced Bionics' Cochlear Implant with Quallion Behind the Ear battery

2004 — Commercial launch of Boston Scientific's Spinal Cord Stimulator with Quallion implanted battery

2012 — **Quallion** registered ISO 9001 &13485; Zero-Volt™ technology patented

Commercial launch (EU) of Sequana Medical's implanted pump with Quallion implanted battery

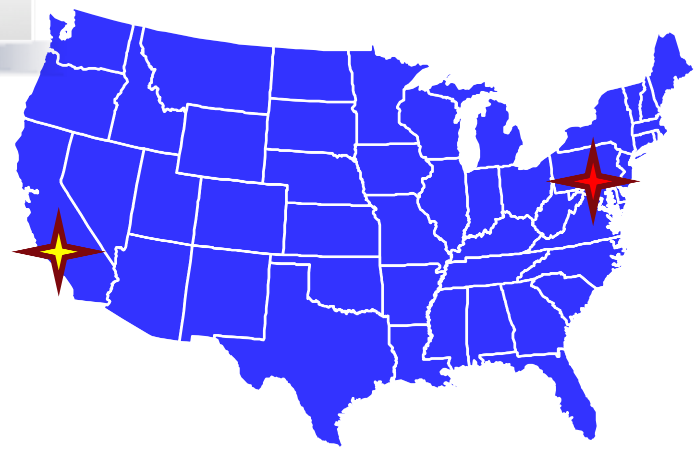
2013 — Manufactured 100,000th implantable medical battery

Impulse Dynamics launches Optimizer IV using Quallion implanted battery

2014 — 10 years of safety and reliability in implanted medical applications

EnerSys acquired Quallion.

Locations:
Quallion Facility- Los Angeles County, CA
EnerSys Headquarters- Reading, PA



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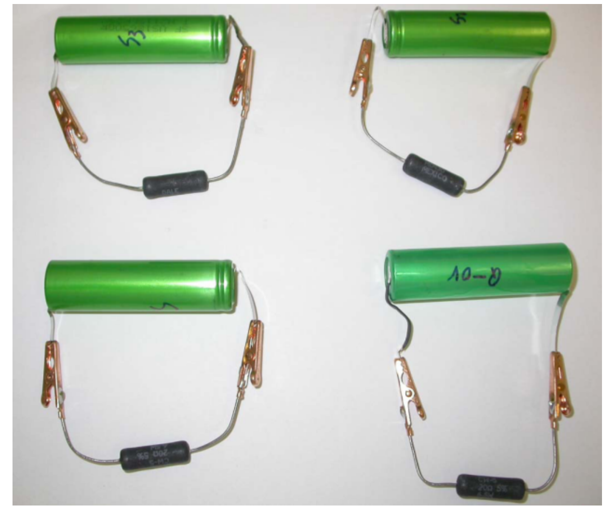
Single Cell Evaluation

1. ZeroVolt chemistry design verification (Comparison with conventional LIB)
2. ZeroVolt cell characterization for aerospace application
   1. 200mAh test cell, 0V storage + LEO cycling test
   2. 15Ah cell, low voltage storage + LEO cycling test
   3. 75Ah cell, low voltage storage + calendar life test

Introduction of ZeroVolt Technology
Comparison with Conventional LIB, Test Method

Test sample cell

- Quallion 18650 cell (Zero-Volt™ technology)
- Sony 18650H2 cell (Hard carbon cell)



Test procedure

1. Capacity check to determine baseline capacity (before storage)

- The cells are cycled three times at room temperature according to the following standard procedures.
  - a) CC charge at C/2 rate to 4.2V
  - b) CV charge at 4.2V with a current cutoff of C/20
  - c) CC discharge at C/2 rate to 2.7V

2. Simulate 0V state by short-circuiting the cell with a 20 ohm resistor.

3. Storage at room temperature for 3 days.

4. Charge the cells at room temperature in two steps

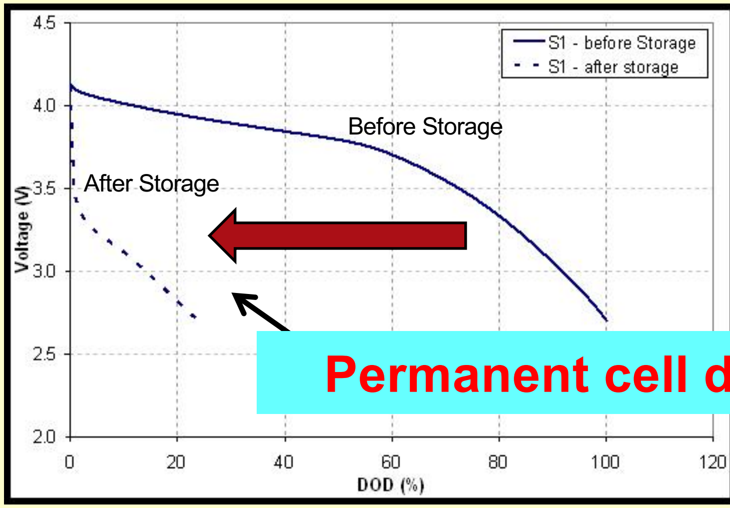
- CC charge at C/200 rate to 3.0V
- CC charge at C/20 rate to 4.2V

5. Repeat the capacity check test from step 1 to determine the cell capacity after 0V storage.

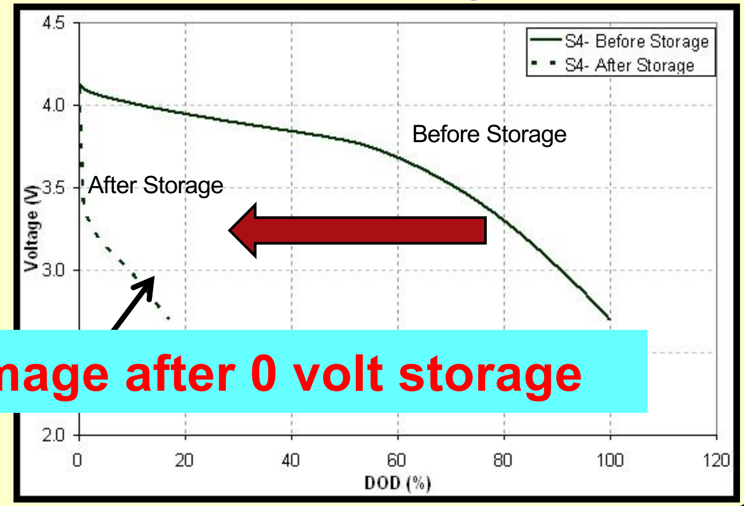
ZeroVolt Cell Characterization
Before and After 3-day Storage at Zero Volt

SONY 18650

Room temperature storage



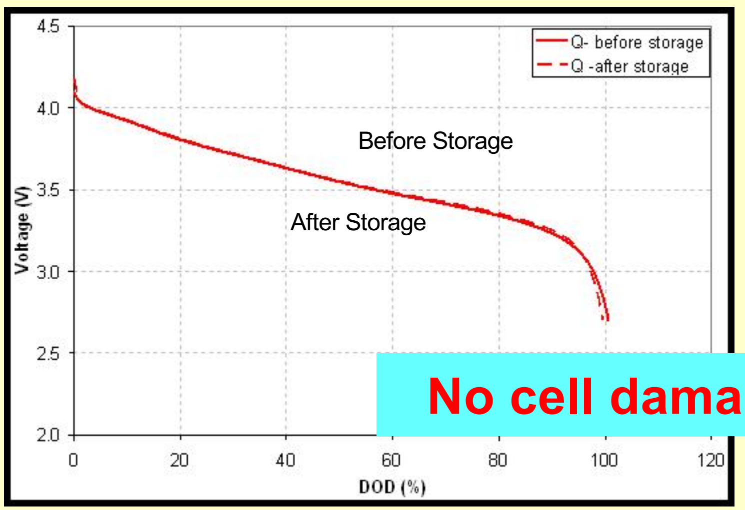
40oC storage



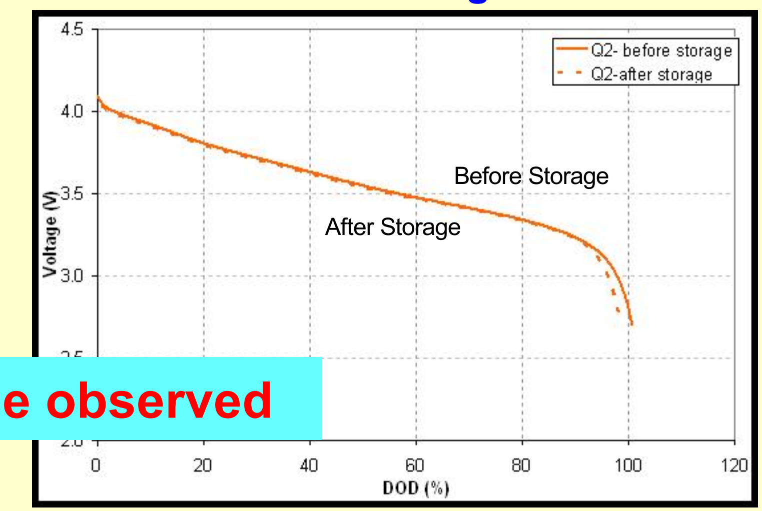
Permanent cell damage after 0 volt storage

Quallion 5A-2 zero-volt 18650

Room temperature storage



40oC storage



No cell damage observed

ZeroVolt Cell Characterization Protocol for Aerospace Application

Test cell

- 200 mAh simulation cell
- Hermetic

50 Ω resistor attached across the positive & negative terminals of SCS cell

- **Pre-0V storage**
  1. Take ACIR/OCV measurements
  2. Capacity Check Cycling (2 cycles)
     1. Charge: CCCV 0.5C to 4.1 V, 0.05 C cutoff @ 23 °C
     2. Rest: 10 minutes
     3. Discharge: 0.5C to 2.7 V @ 23 °C
     4. Rest 10 minutes
- **0V storage**
  1. Characterization for Zero Volt Storage
     1. Discharge: 0.05C to 2.7 V @ 23 °C
     2. Rest 10 minutes
  2. Attach 50 Ω resistor across positive & negative terminals of SCS cells
     - Incubator storage @ 23 °C for **14 or 29 months**
- **Post-0V storage**
  1. Remove 50 Ω resistor from SCS terminals
  2. Recovery from Zero Volt Storage, Characterization
     1. Charge: CCCV 0.005C (C/200) to 3.0 V @ 23 °C
     2. Charge: CCCV 0.05C (C/20) to 4.1 V @ 23 °C
     3. Rest: 10 minutes
     4. Discharge: 0.5C to 2.7 V @ 23 °C
     5. Rest 10 minutes
  3. Run 2 cycles of capacity check
     1. Charge: CCCV 0.5C to 4.1 V, 0.05C cutoff @ 23 °C
     2. Discharge: CC 0.5C to 2.7 V @ 23 °C
  4. Proceed to long-term cycling tests

Zero Volt Cell Characteristics in Aerospace Use
40% DOD LEO Cycle Performance after 0V Storage (29 months)
(200mAh wound type model cell)

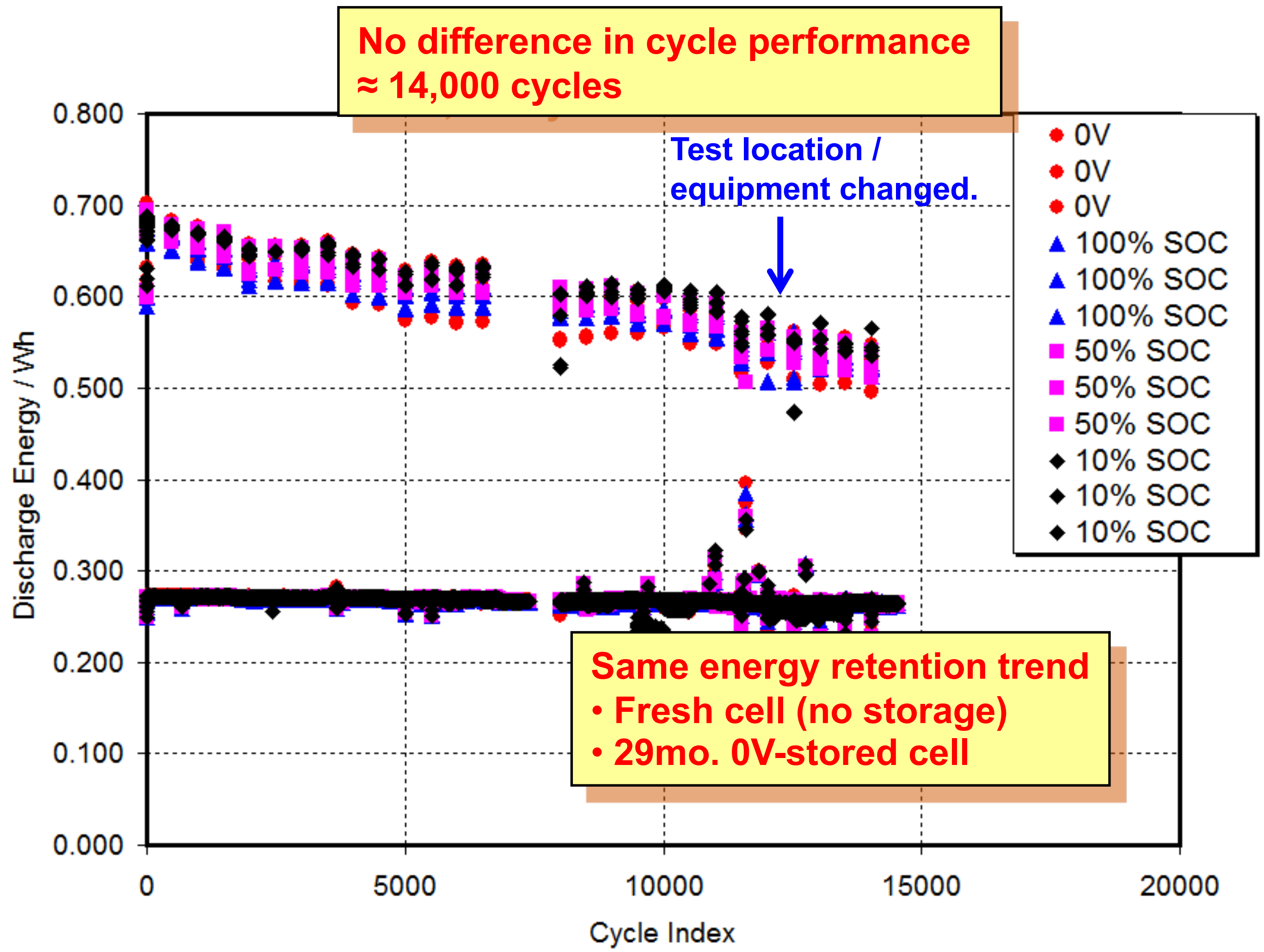
Storage Condition
For **29 months**,
- 100% SOC (3 cells)
- 50% SOC (3 cells)
- 10% SOC (3 cells)
- 0V (3 cells)

(at room temperature)

Cycle condition
- LEO cycle (40% DOD)

Capacity check
- 100% DOD
  at every 500 cycles

(at 20°C)



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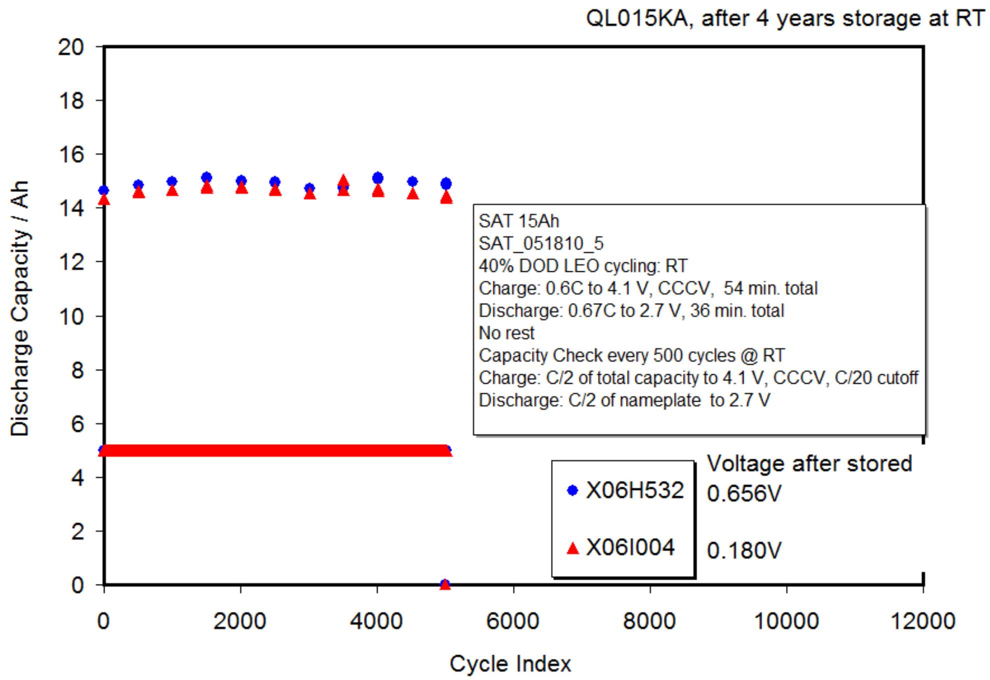
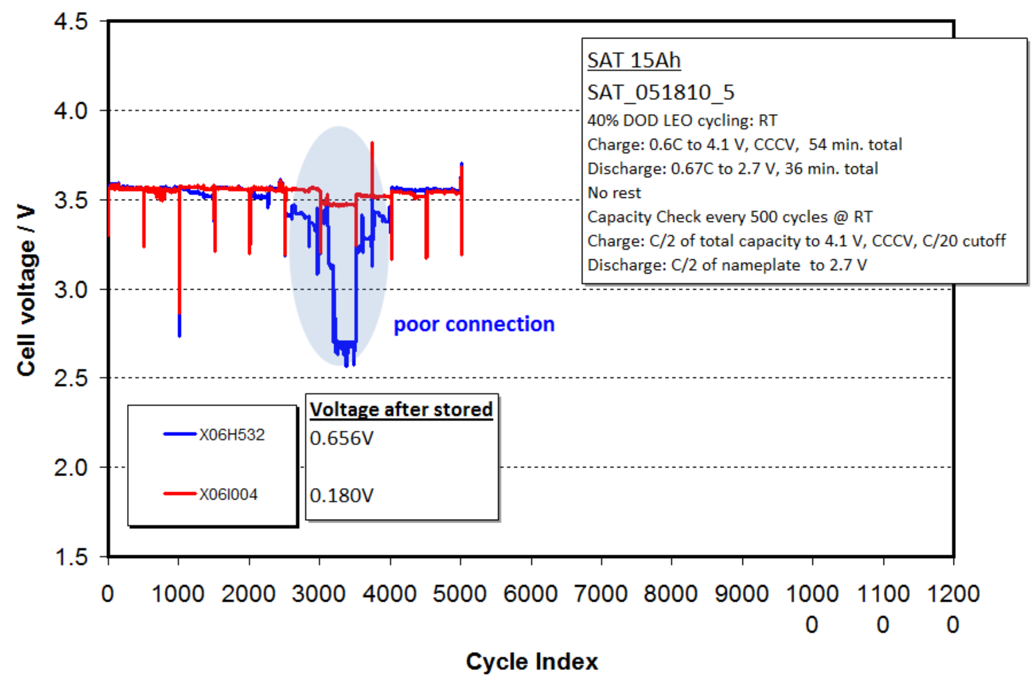
Zero Volt Capability
Capacity Retention and Cell Voltage after 0V Storage (49 months)
(QL015KA cell, 40% DOD LEO Cycle Performance)

	Cell Voltage during Storage / Volts	Discharge Capacity / Ah		
		Before Storage	After Storage (49 months)	After 5000 cycles
X06H532	0.656	14.6	14.6	14.9
X06I004	0.180	14.7	14.4	14.5

Discharge Capacity



Cell Voltage @ End of Discharge



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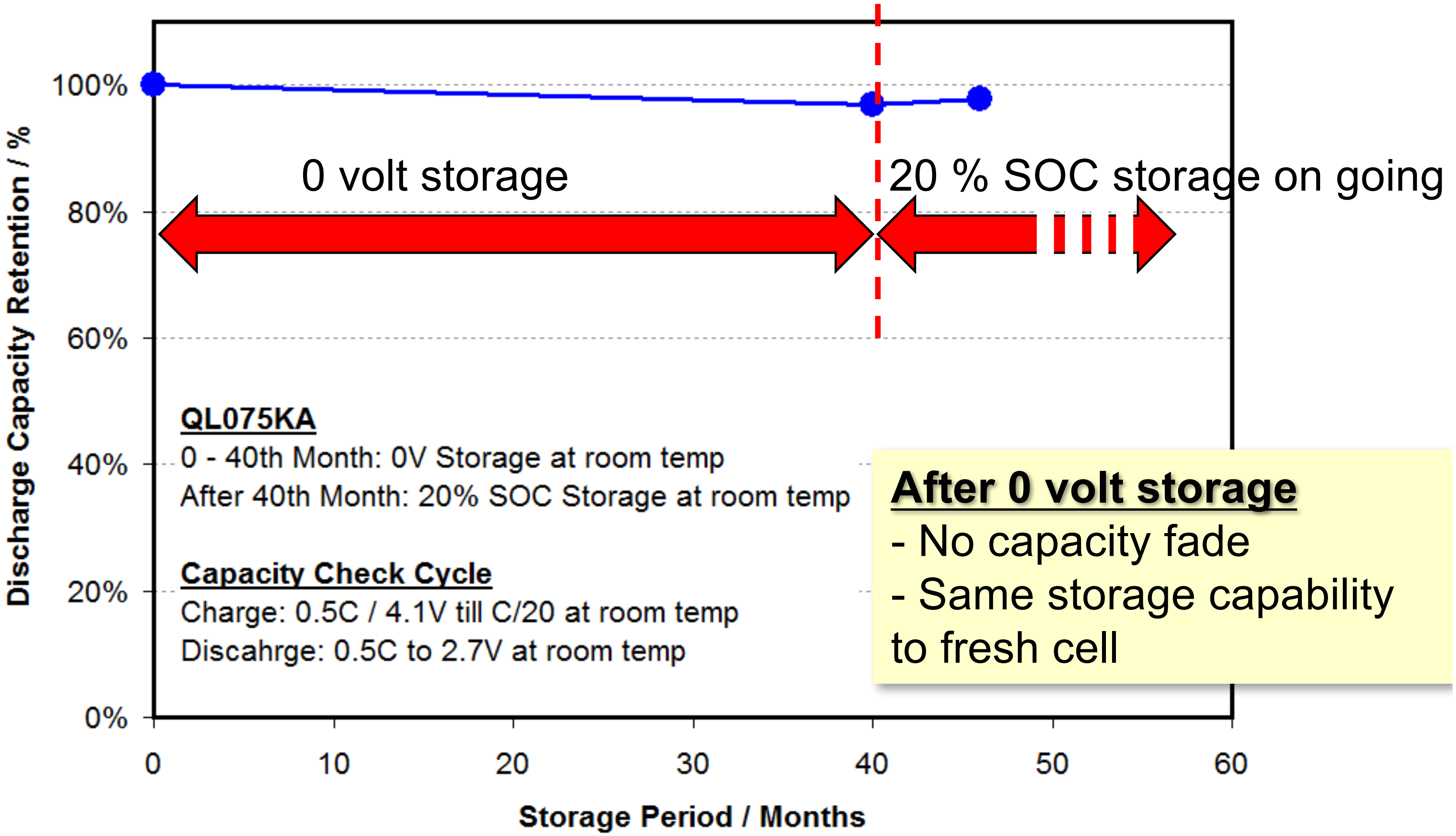
Zero Volt Capability
Capacity Retention after 0V Storage (40 months)
(QL075KA cell, 20% SOC Storage Performance)



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8 Series Module (200 mAh Test Cell) Characterization

1. 0V storage characterization for 4 months
2. Module characterization during 20% DOD LEO cycling after 0V storage

Scope of Work

1. **To perform 0V storage with 200mAh simulation module configured in series of 8 cells***

2. **To understand the influence of 0V storage with module configuration to electrochemical performance at pre-/post- 0V storage**

3. **To characterize the 8-cell module in 20% DOD LEO cycling after 0V storage**

*Cell level characterization of 0V storage has been done separately. This study is extension of understanding 0V capability with ZeroVolt chemistry in application use.

8S 200mAh Test Module Preparation

Cell Configuration & History of cells selected for 0 V Study:

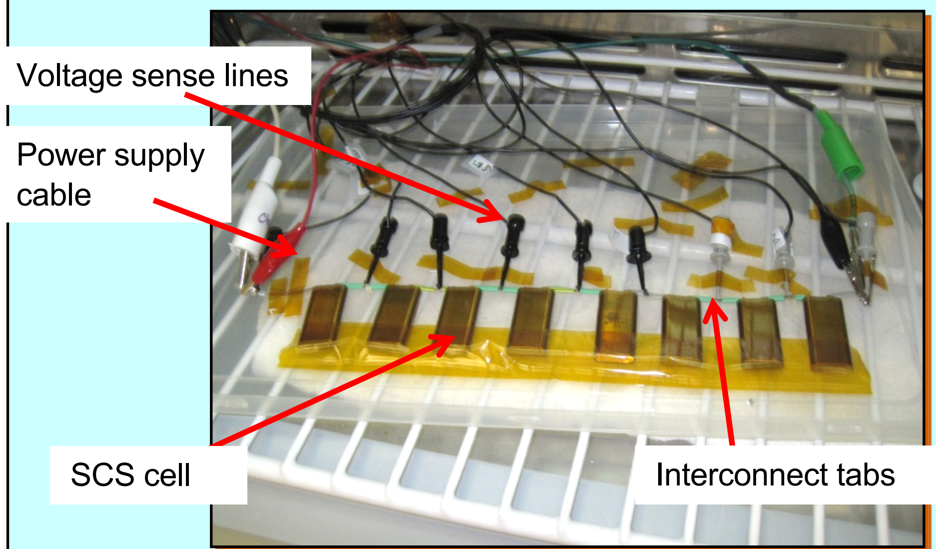
- Form factor: 200mAh simulation cell (SCS cell)

- Feb ~ Mar/2010: Cell Assembly:

(Cells under storage at 3.64 - 3.67 V for ~ 2 years before Module assembly and Module 0V storage characterization)

- Jan/2012: Module Assembly
- Jan ~ May/2012: 0V storage
- Jun/2012~: 20% DOD LEO cycling

8S Module Assembly



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8S 200mAh Test Module
0V Characterization Protocol

1. Take ACIR/OCV measurements

2. Capacity Check Cycling (2 cycles)

1. Charge: CCCV 0.5C until first cell reaches 4.1 V, C/20 cutoff @ 23 °C
2. Rest: 10 minutes
3. Discharge: 0.5C until first cell reaches 2.7 V @ 23 °C
4. Rest 10 minutes

3. DCIR Test (1 cycle)

1. Charge: CCCV 0.2C until first cell reaches 4.1 V, C/20 C cutoff @ 23 °C
2. Rest: 10 minutes
3. Discharge: 0.2 C for 30 minutes or to 2.7 V @ 23 °C
4. Pulse: 1C for 5 seconds
5. Repeat Discharge and Pulse until first cell reaches 2.7 V

4. Characterization for Zero Volt Storage

1. **Discharge: 0.1C until first cell reaches 0 V @ 23 °C**
2. Rest: 1 hour
3. Take ACIR/OCV measurements
4. **Attach resistance across positive & negative terminals of module**
   - **8S module: 400 Ω resistance (= 50 Ω per cell)**

5. Incubator storage @ 23 °C for specified period

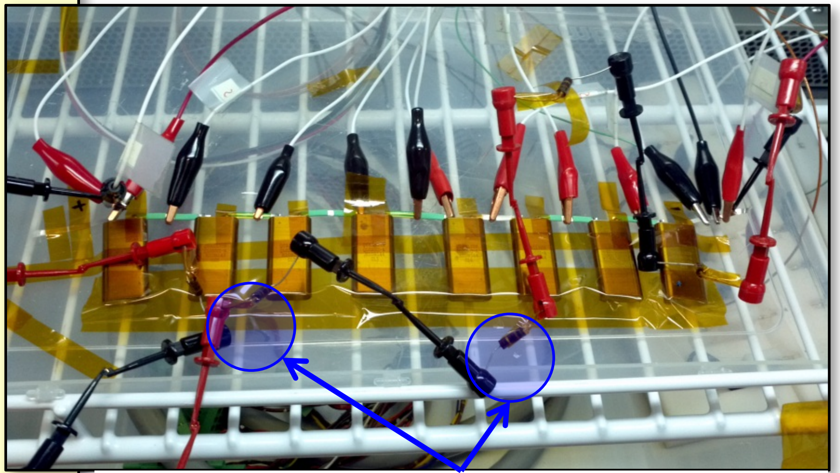
6. Recovery from 0V storage

1. After removing resistors, take ACIR/OCV measurements
2. Charge: CC C/200 until first cell reaches 3.0 V
3. Charge: C/20 until first cell reaches 4.1 V
4. Discharge: CC 0.5C until first cell reaches 2.7 V

7. After 4 months, 0V storage, place modules on 20% DOD, LEO Cycling

Current across module with 2.7 V / cell when resistors are attached does not exceed 0.3 C rate

8S Module under 0V Storage



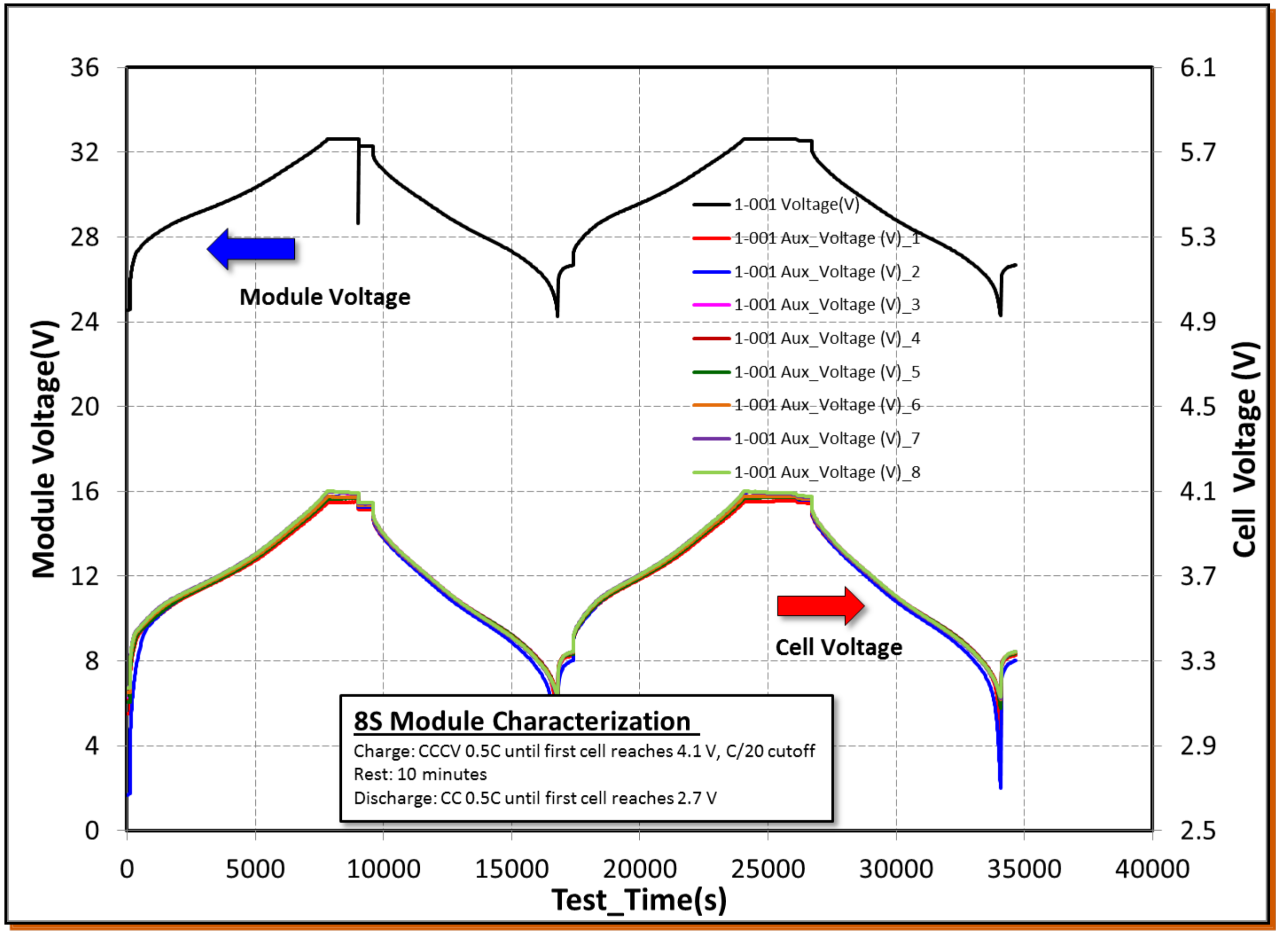
50 Ω resistors in series across module terminals

0V storage characterization for 4 months

Characterization of Modules before 0V Storage, Month 4
Capacity Check Cycling, 8S Modules

8S Module, Module and Cell Voltage

- **Capacity Check Cycling (2 cycles)**
  1. Charge: CCCV 0.5C until first cell reaches 4.1 V, C/20 cutoff @ 23 °C
  2. Rest: 10 minutes
  3. Discharge: 0.5C until first cell reaches 2.7 V @ 23 °C
  4. Rest 10 minutes



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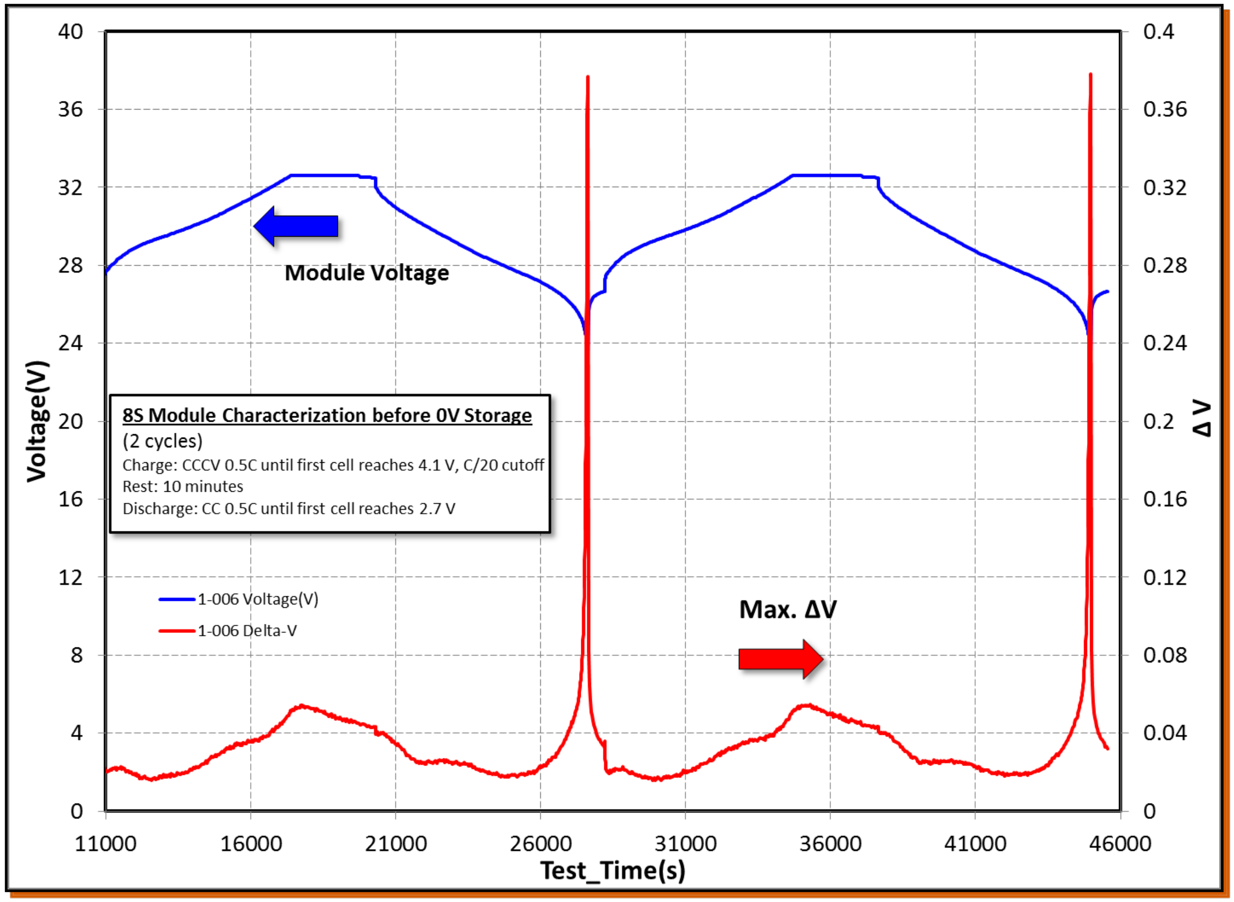
Characterization of Modules before 0V Storage

Capacity Check Cycling, 8S Modules, Month 0

8S Module, Voltage and ΔV* vs. Time

ΔV defined as the max. difference between cell voltages during cycling

- **Capacity Check Cycling (2 cycles)**
  1. Charge: CCCV 0.5C until first cell reaches 4.1 V, C/20 cutoff @ 23 °C
  2. Rest: 10 minutes
  3. Discharge: 0.5C until first cell reaches 2.7 V @ 23 °C
  4. Rest 10 minutes



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Modules after 0V Storage, Months 0 - 4

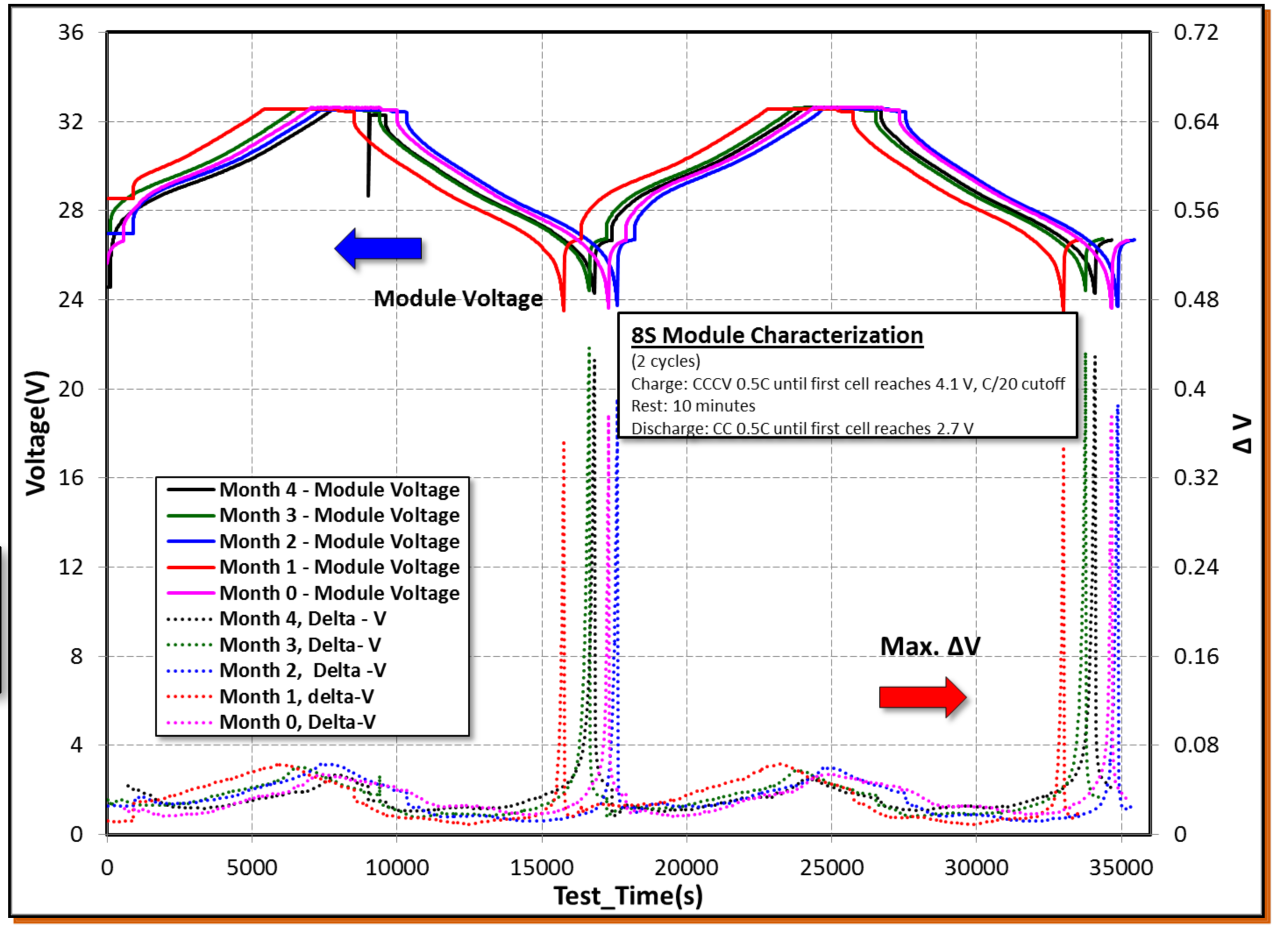
Capacity Check Cycling, 8S Modules

8S Module, Voltage and ΔV* vs. Time

* ΔV defined as the max. difference between cell during cycling

- **Capacity Check Cycling (2 cycles)**
  1. Charge: CCCV 0.5C until first cell reaches 4.1 V, C/20 cutoff @ 23 °C
  2. Rest: 10 minutes
  3. Discharge: 0.5C until first cell reaches 2.7 V @ 23 °C
  4. Rest 10 minutes

Max. ΔV among 8 cells were in 8S module:
- @ 50% DOD = 10 – 25 mV
- @ 100% DOD, 2.7 V = 360 – 480 mV



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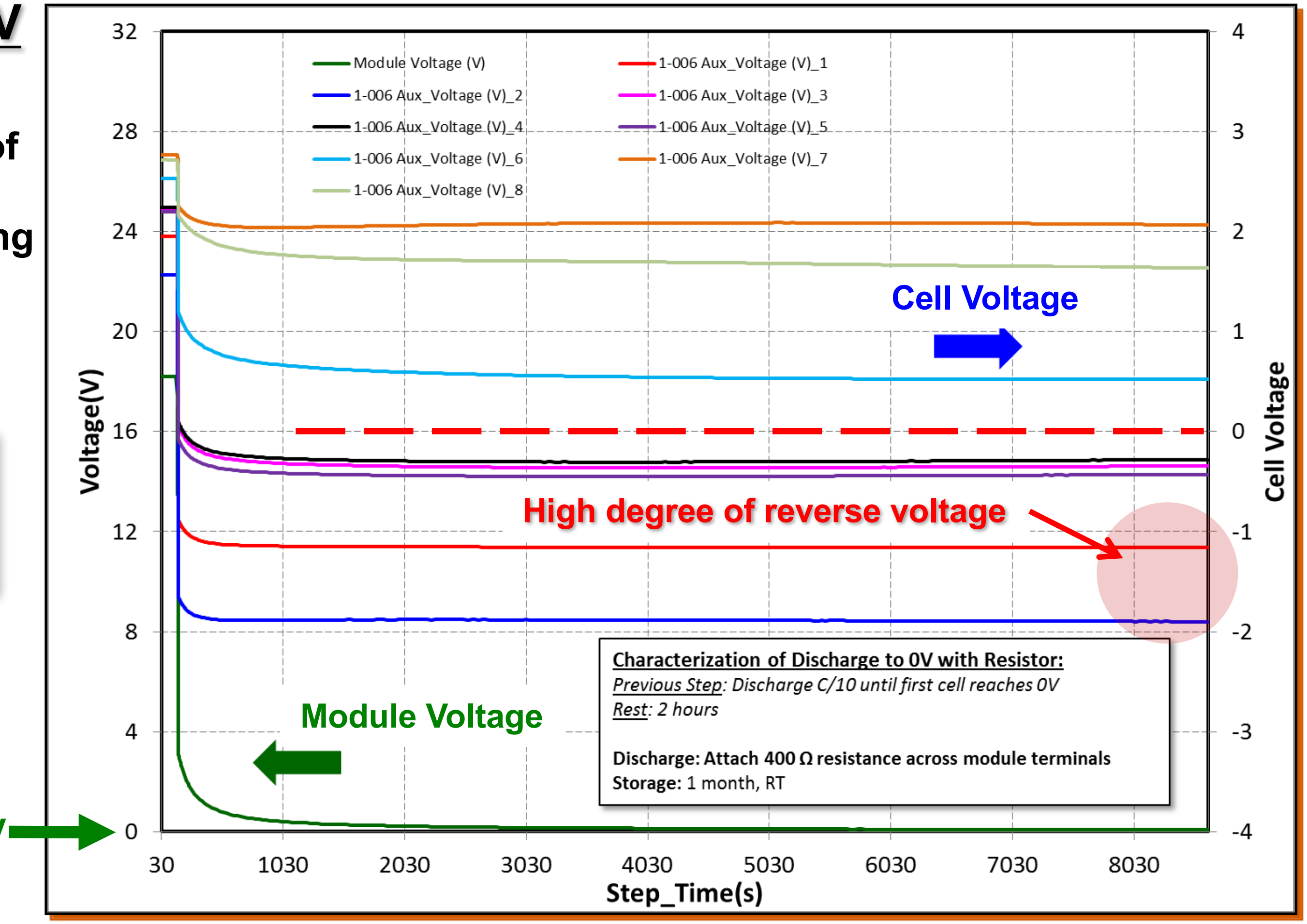
Characterization of Modules after 0V Storage
8S Modules, Month 0
Cell Voltages during 0V Storage in Modules *

8S Module, Discharge to 0V

*** Voltage profile after attachment of resistors across positive and negative terminals of module during first month of 0V storage**

→ 8S module:
2 cells showed reverse voltage between -1 V and -2 V.



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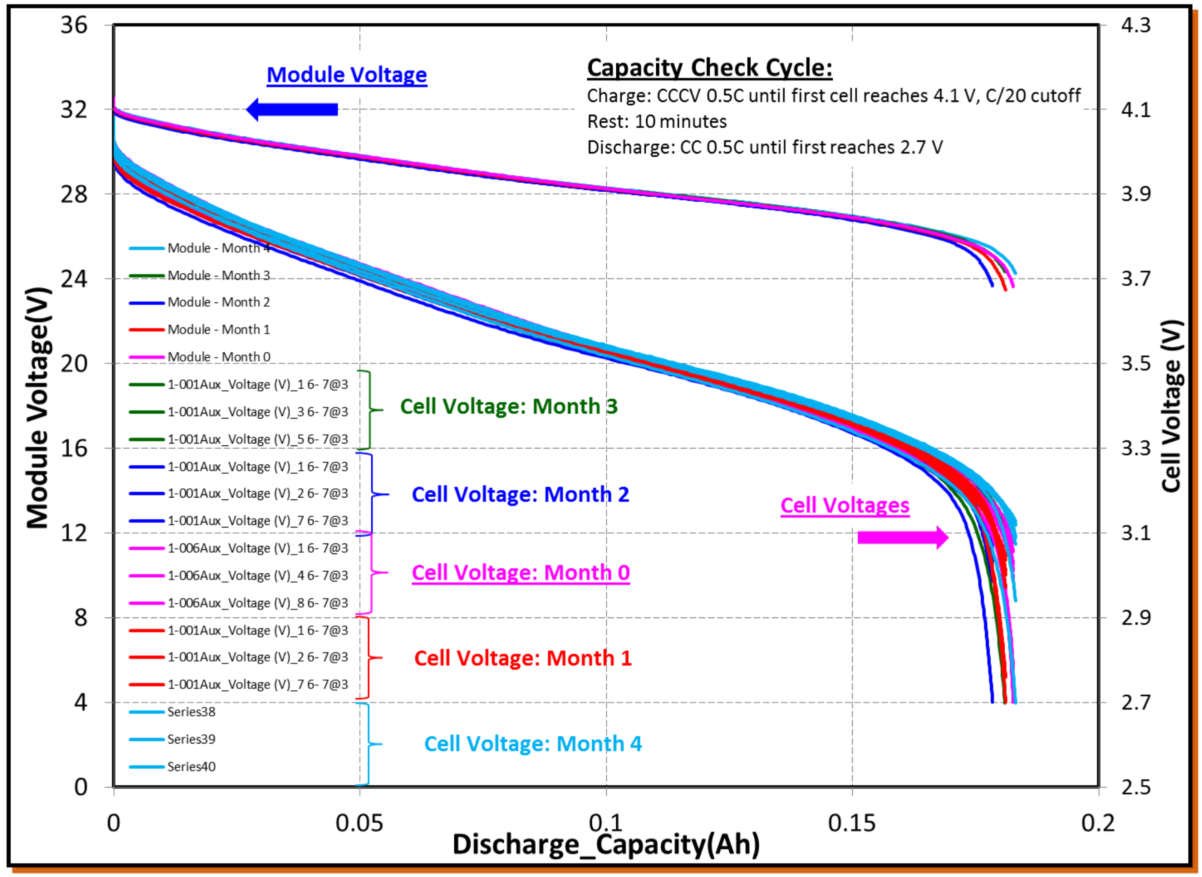
Characterization of 8S Modules after 0V Storage
Discharge Curve Comparison in Month 0, 1, 2, 3, and 4

Discharge Curves

- **Capacity Check Cycling Condition**
  1. Charge: CCCV 0.5C until first cell reaches 4.1 V, C/20 cutoff @ 23 °C
  2. Rest: 10 minutes
  3. Discharge: 0.5C until first cell reaches 2.7 V @ 23 °C
  4. Rest 10 minutes

Discharge Capacity Retention, 8S Module:
No change during 0V storage

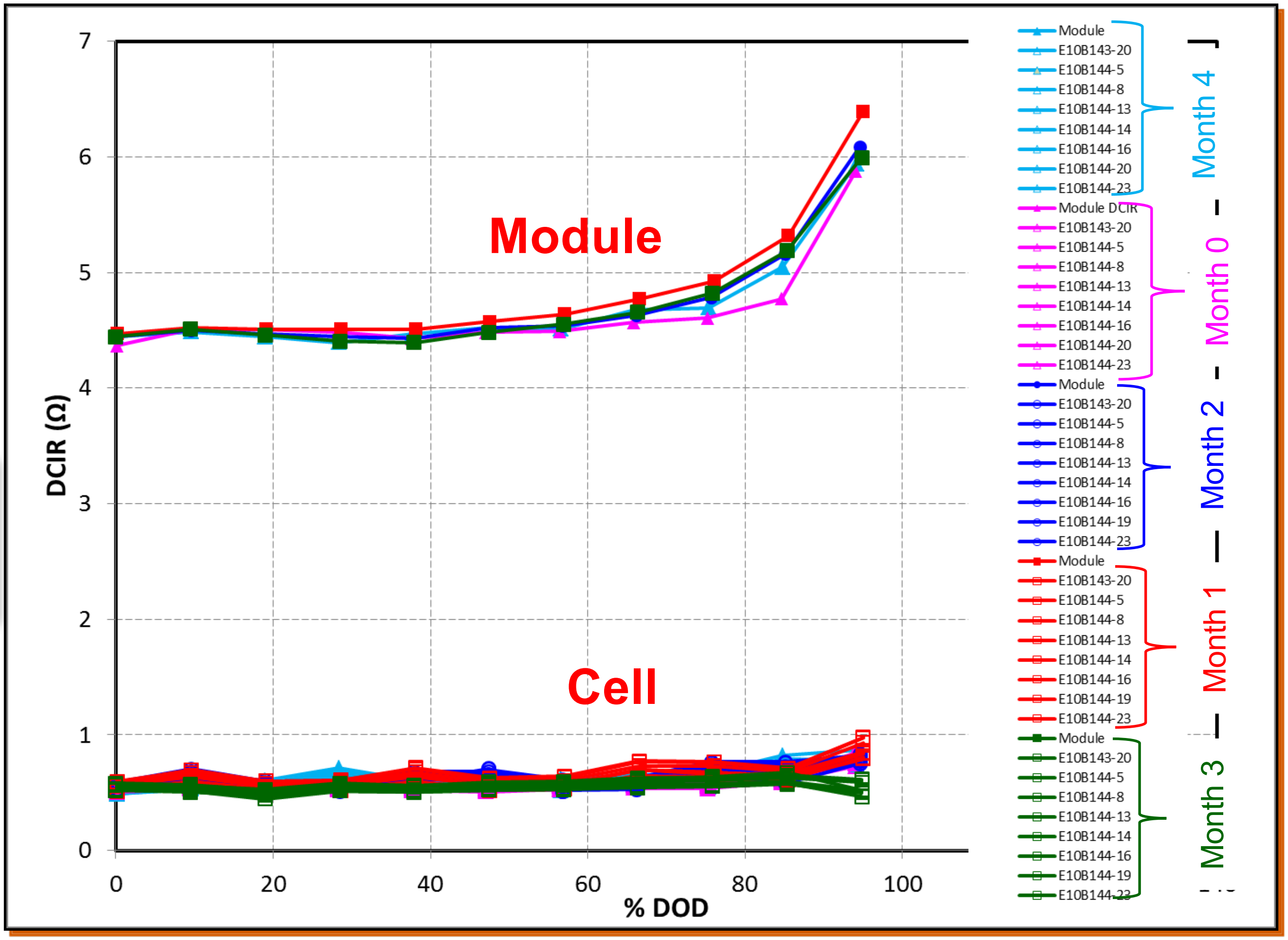


Characterization of 8S Modules after 0V Storage
DC Resistance Dependency on DOD

DC resistance vs. Depth-of-Discharge

- DC restance test (1 cycle)
  1. Charge: CCCV 0.2C until first cell reaches 4.1 V, C/20 C cutoff @ 23 °C
  2. Rest: 10 minutes
  3. Discharge: 0.2 C for 30 minutes or to 2.7 V @ 23 °C
  4. Pulse: 1C for 5 seconds
  5. Repeat Discharge and Pulse until first cell reaches 2.7 V

→ DC-IRs at any DOD did not show any change after 0V, 4 months in 8S module.



8S 200 mAh Test Cell Module, 0V Storage Performance Summary

During 0V storage for 4 months, the following were found at periodic characterization (capacity check cycles):

Discharge Capacity:

100% discharge capacity retention for 4 months at 0V

- Discharge capacity: from 0.183 Ah to 0.183 Ah

Maximum ΔV:

No change in voltage divergence among 8 cells

- Max ΔV @ 100% DOD= 360 – 480 mV
- Max. ΔV @ 50% DOD = 10 – 25 mV

DCIR:

No change in DC resistance across a range of DOD during 0V storage for 4 months

AC-IR:

No change in AC-IR values was observed.

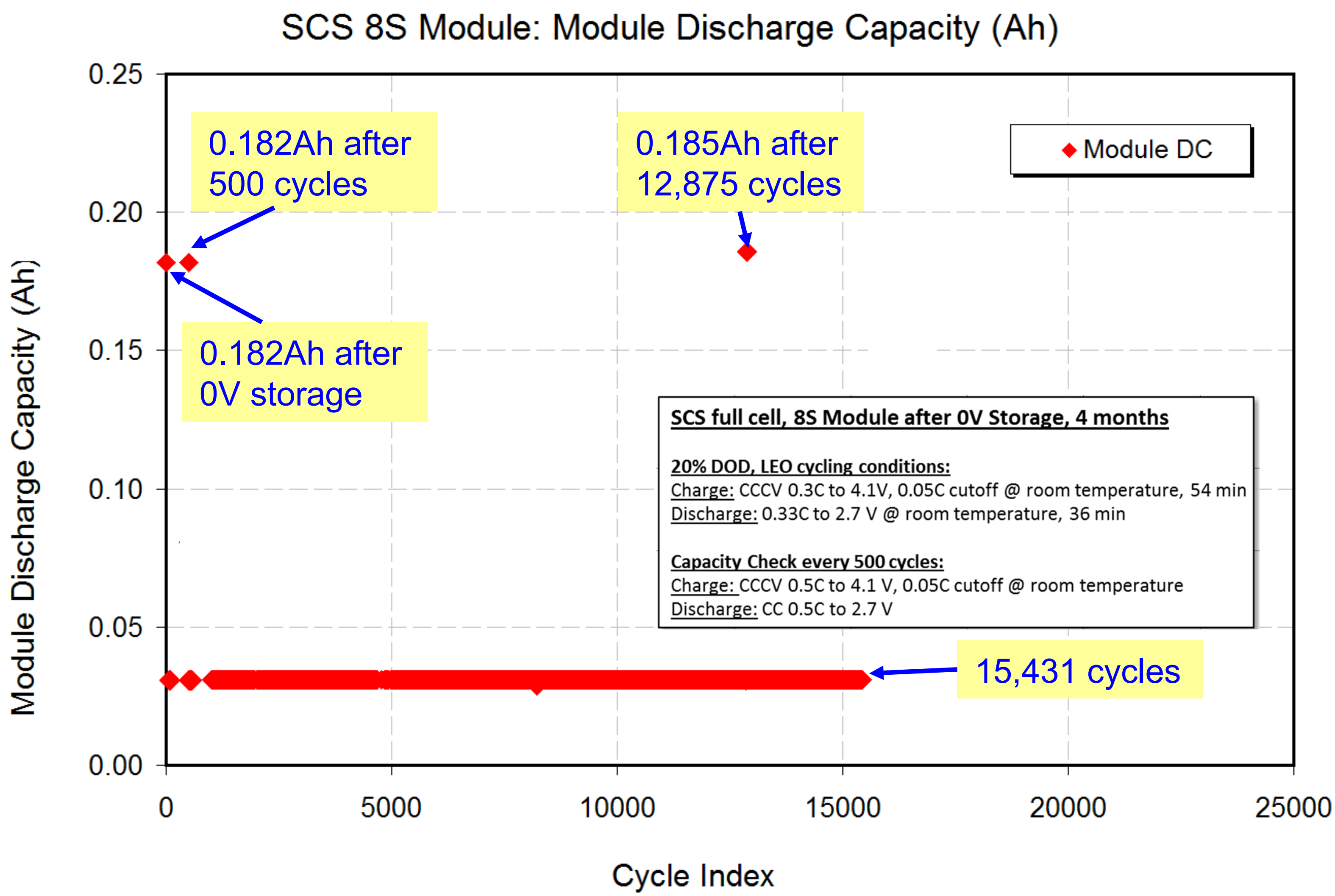
➔ The test module demonstrated the 0V storage capability without any degradation.

8S Module characterization during 20% DOD LEO cycling after 0V storage

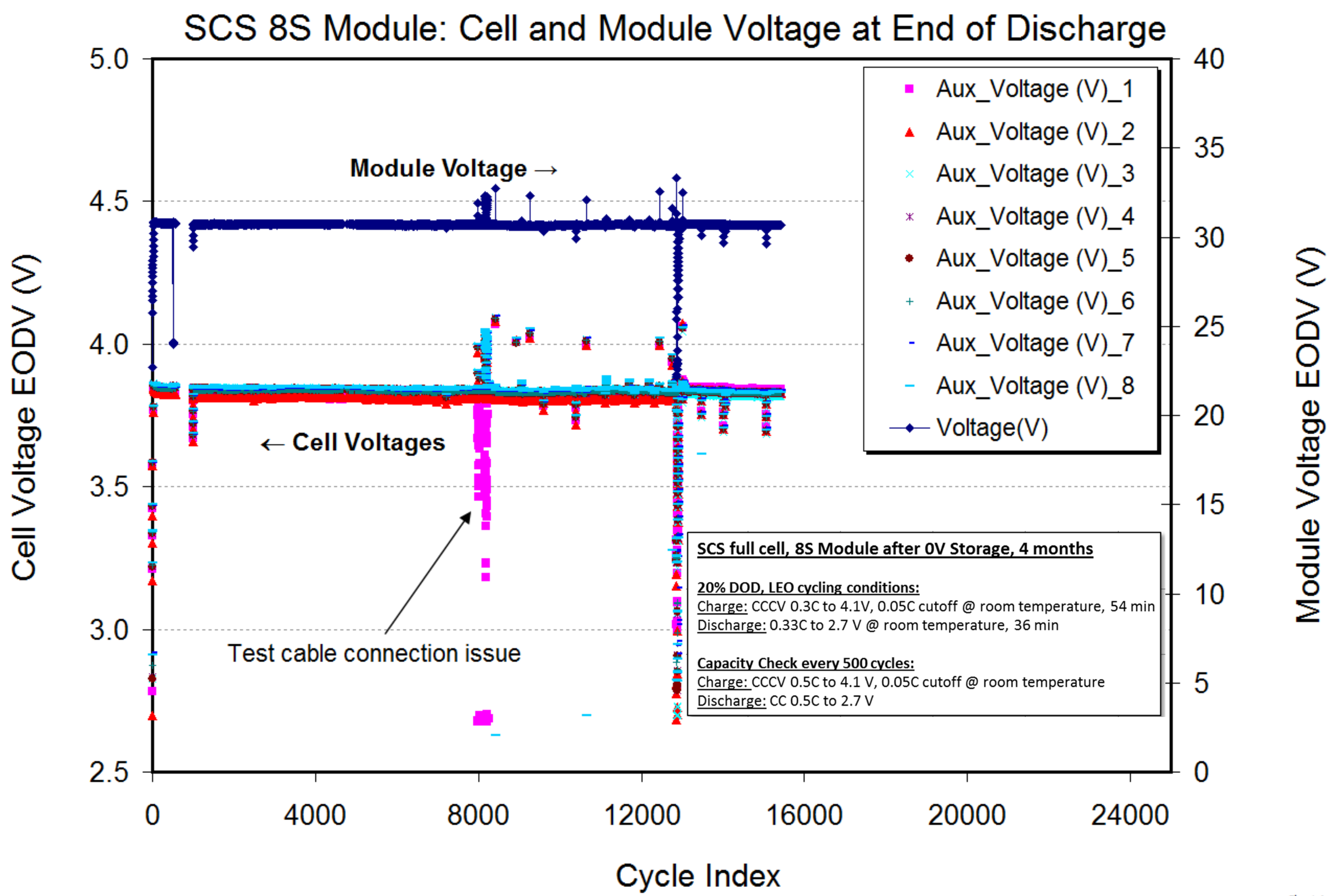
(15,431 Cycles as of Nov. 2016)

8S Module Characteristics under 20% DOD LEO Cycling after 0V Storage
Discharge Capacity and End-of-Discharge Voltage

Discharge Capacity



8S Module Characteristics under 20% DOD LEO Cycling after 0V Storage Discharge Capacity and End-of-Discharge Voltage



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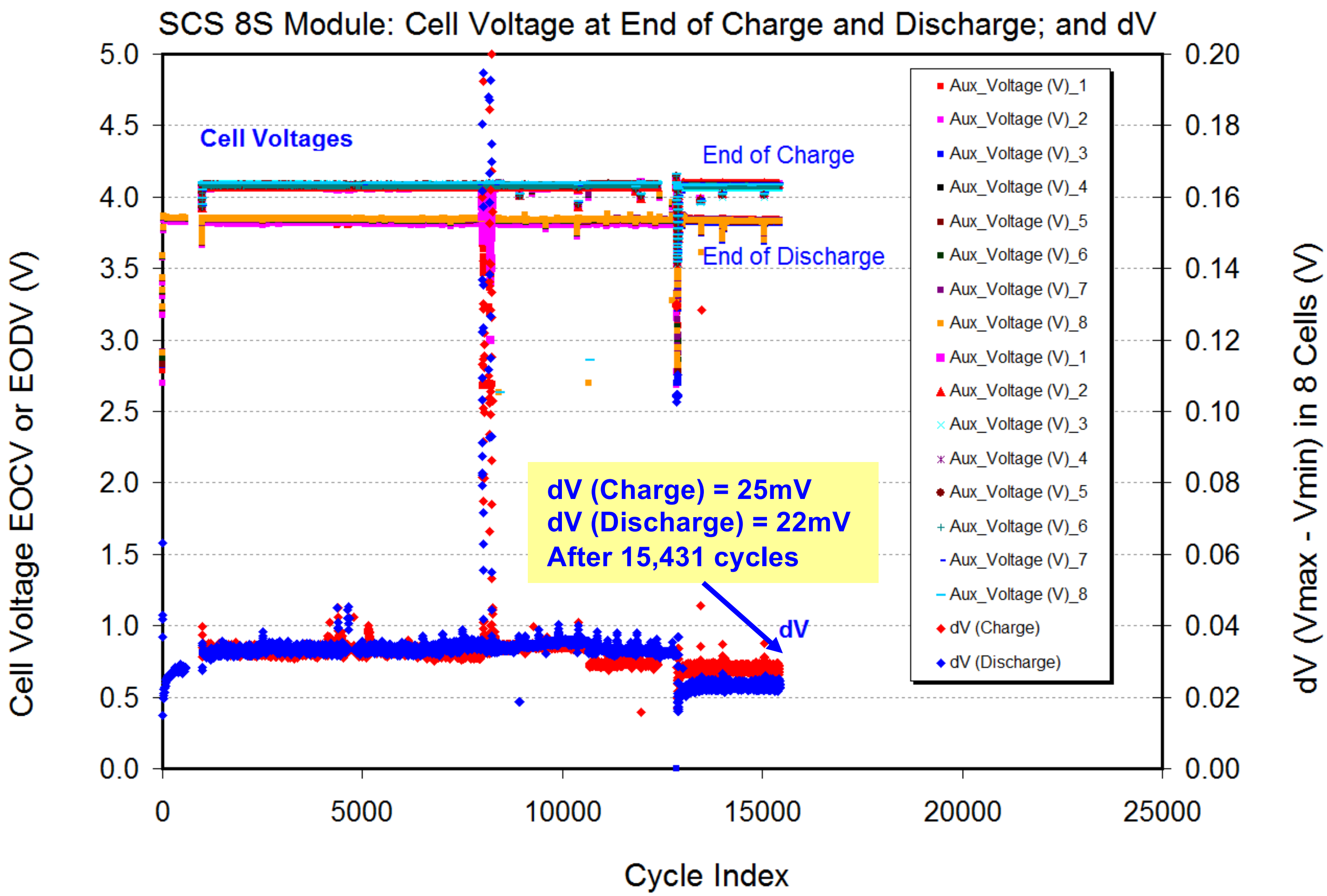
8S Module Characteristics under 20% DOD LEO Cycling after 0V Storage
Maximum ΔV between Cells at End-of-Discharge Voltage

End-of-Discharge Voltage



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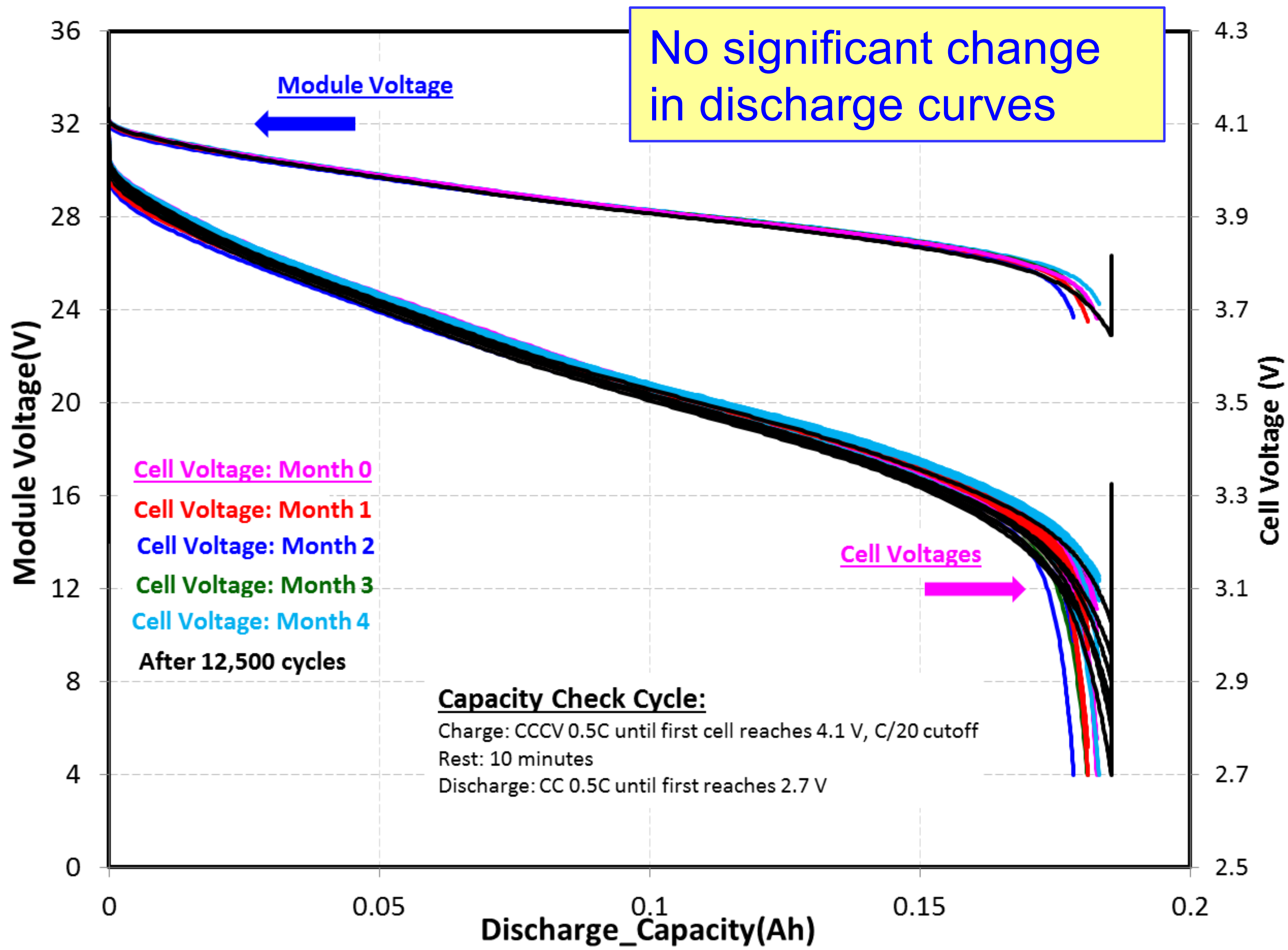
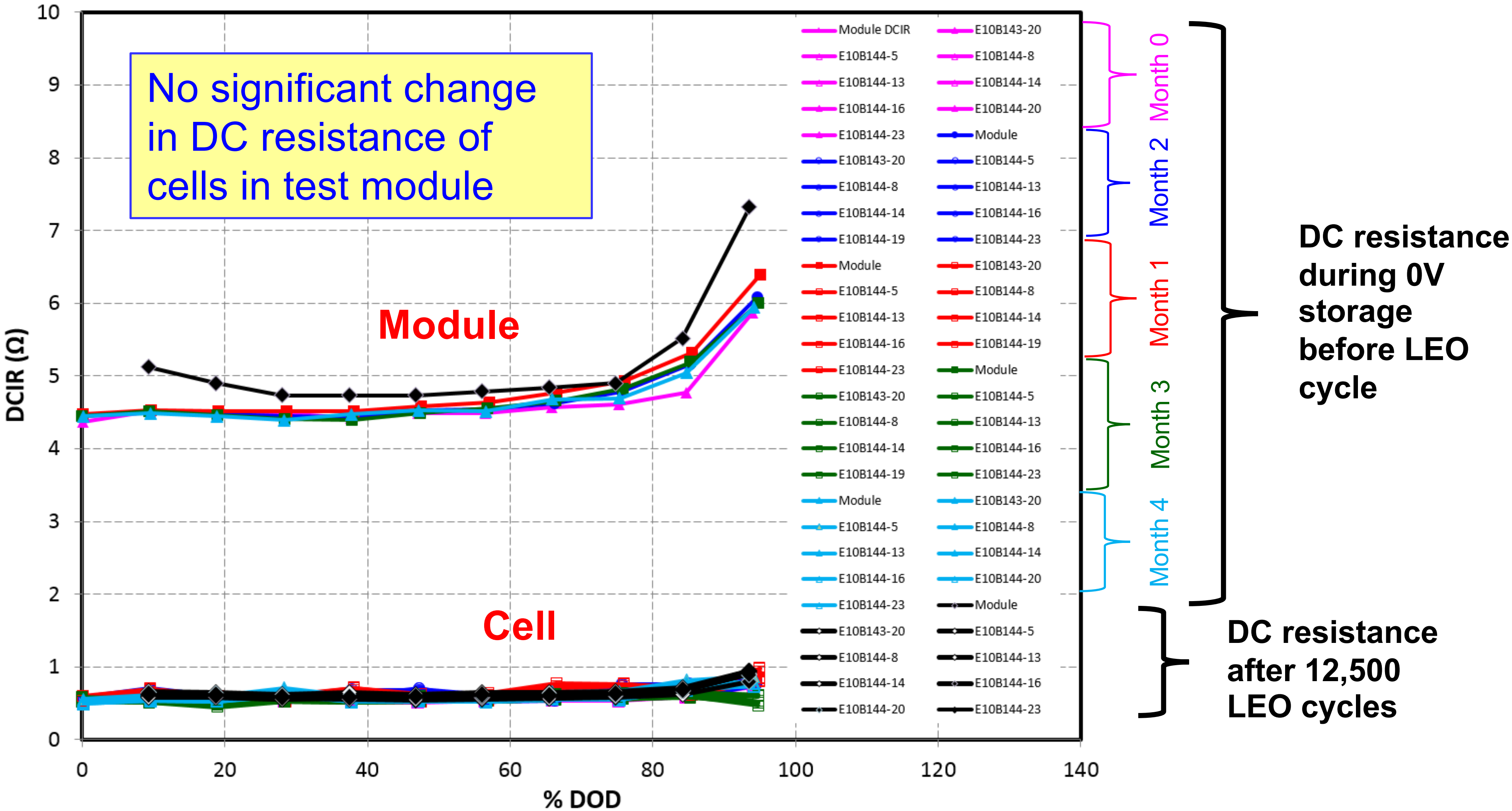
8S Module Characteristics under 20% DOD LEO Cycling after 0V Storage
Cell and Module Discharge Curves



8S Module Characteristics under 20% DOD LEO Cycling after 0V Storage
DC Resistance Dependency on DOD



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8S 200mAh Test Cell Module, 20% DOD LEO Cycling Performance Summary

During 20% LEO cycling after 4 months of 0V storage with 8S module, the following were observed:

Discharge Capacity Retention:

No change after 12,500 cycles:

- ❑ Discharge capacity in the 8S module: from 0.183 Ah to 0.185 Ah

Maximum ΔV during cycling:

No significant increase of cell voltage divergence in module during 15,451 cycles

- ❑ Max ΔV @ end of charge = 25 mV
- ❑ Max. ΔV @ end of discharge = 22 mV

DCIR:

No change in DC resistance of cells across a range of DOD after 12,500 cycles

➔ The test module demonstrated the superior LEO cycling performance for aerospace application after 0V storage.

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