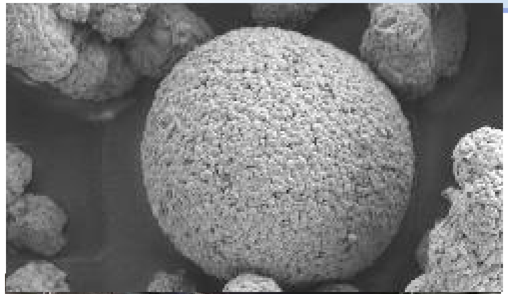
Zero-Volt-Capable Cells for Resilient, Long-Lived LEO Batteries



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Outline

- ➢ Introduction to CAMX Power
  - CELX-RC® Li-ion Cell Technology
- ➢ 0V-capable Satellite Battery Cell Development
  - Background
  - LTO-anode Cells
  - Graphite-anode Cells
- ➢ Conclusions

Introduction to CAMX Power

CAMX Power is a small business with vertically integrated battery development capability

Materials Development → **Materials Scale-Up** → **Electrode & Cell Development** → **Cell Production &Testing** → **Prototyping of Packs**

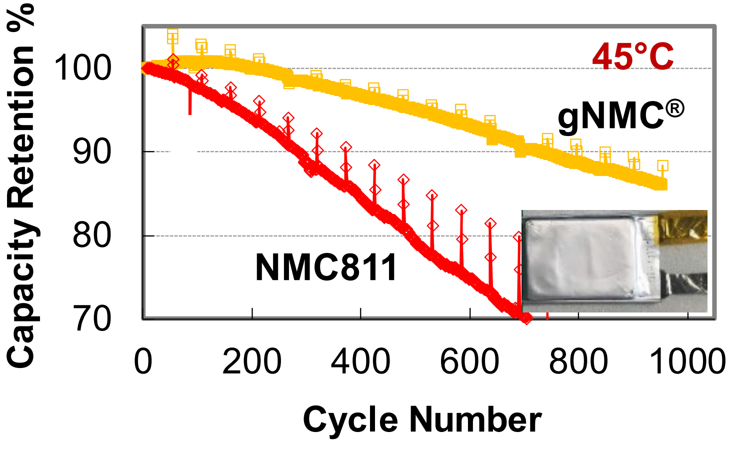
CAMX Power Battery Technology Innovations & Offers

CAM-7® cathode material platform

- Non-exclusive to BASF and Johnson Matthey (2016)

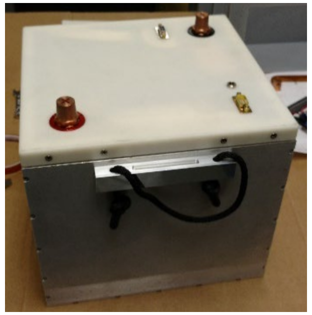
GEMX® cathode material platform

- Non-exclusive license to **LG Energy Solution (2022)**, **Samsung (2020)**, **Johnson Matthey (2018; sold to EV Metals 2022)**
- Additional license discussions ongoing



Rugged and safe Li-ion battery – CELX-RC®

- Limited production and/or licensing for DOD applications



Technologies for detection of internal short circuits in Li-ion batteries

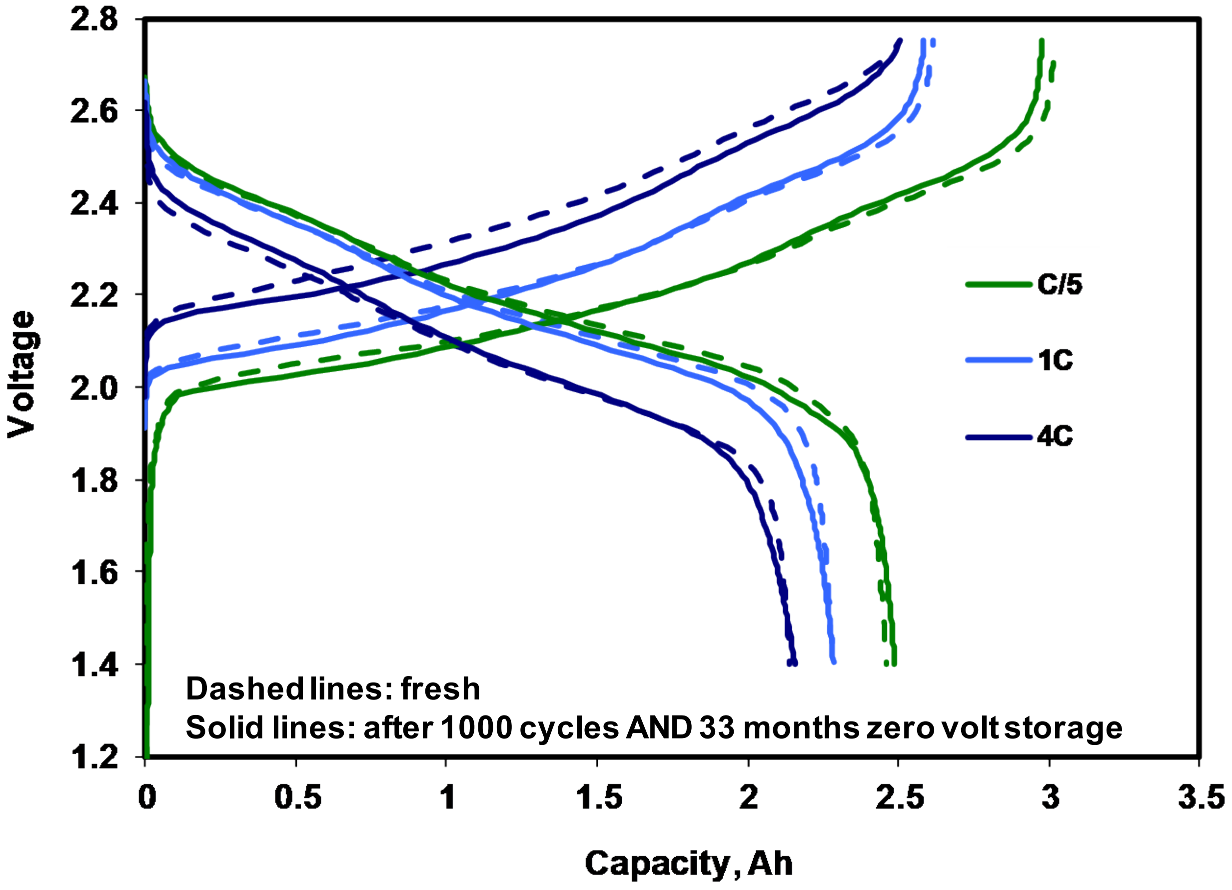
- Cell screening for production QC (screened >40,000 cells for US Navy and NASA, and sold screening units to NASA)
- In-pack short detection (being adapted for Navy UUVs)

Time for detecting 125kΩ internal short	Standard Measurement*	CAMX Technology
	14 days	< 2 hours

CAMX Power has developed CELX-RC® Li-ion cell chemistry for specialized applications.

- **CELX-RX cell chemistry combines:**
  - gLNO® high-Nickel cathode material
  - LTO (lithium titanate) anode material
  - Engineered electrolyte
- **Cell chemistry is capable of:**
  - Multiple discharges to 0 Volts
  - Operating without management electronics
  - Charging and discharging at -60°C
- **Key stability/safety attributes include:**
  - Exceptional mechanical abuse tolerance
  - Excellent thermal tolerance
- **Cell chemistry implemented in:**
  - Laminate pouch cells of up to 10 Ah size
  - 18650 (1.8 cm d, 6.5 cm l) cylindrical cells

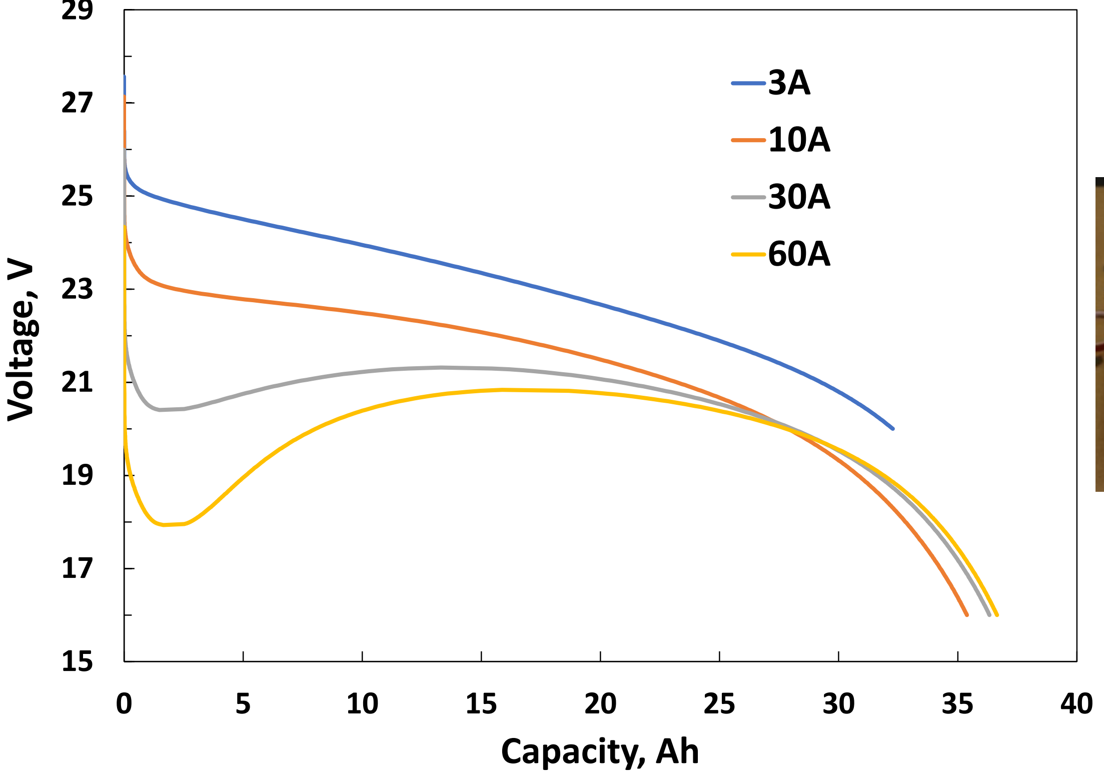
2.5 Ah CELX-RC Pouch Cell Cycled 1000X and Stored at 0V for ~ 3 years

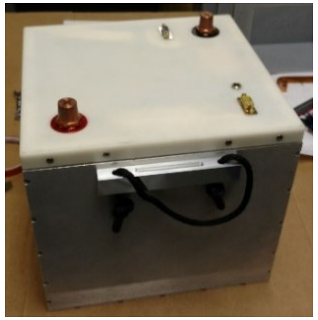


6T prototype demonstrates exceptional low-temperature capability after 24 hours equilibration at -63 °C.

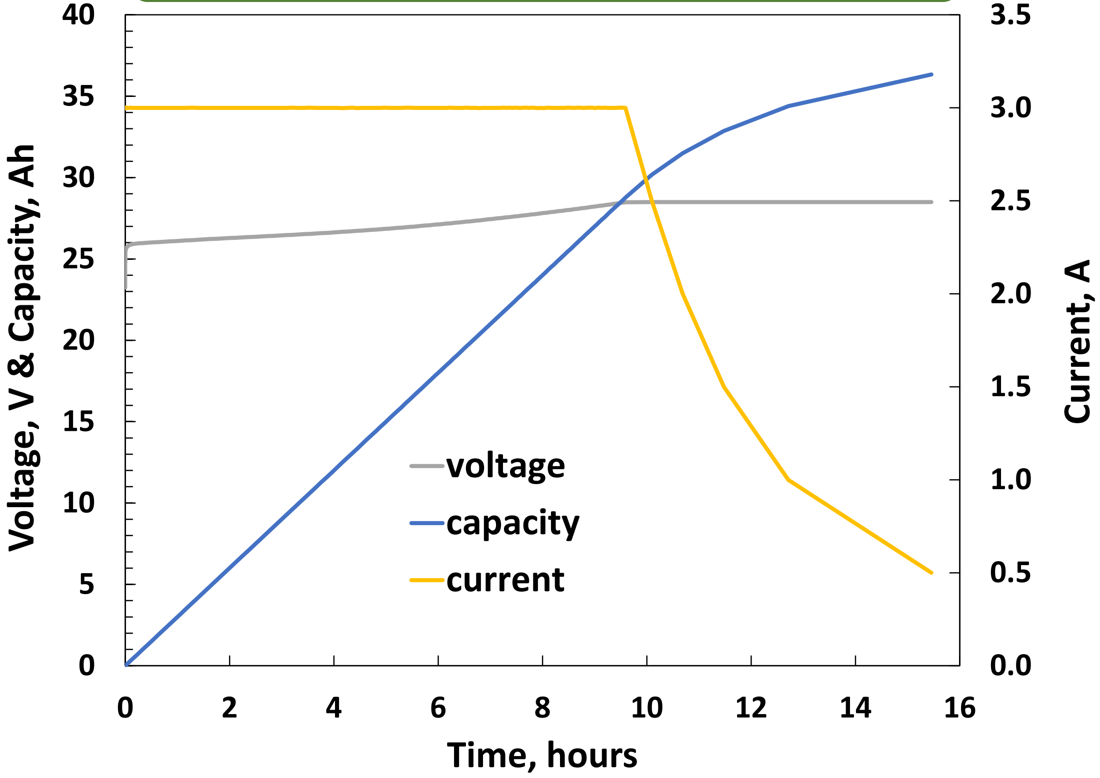
- For 30A (C/2) and higher discharge rates, battery self-heating helps sustain performance.
- Following discharges at -63 °C, battery can be fully recharged in freezer.

6T Prototype: Discharges at -63 °C



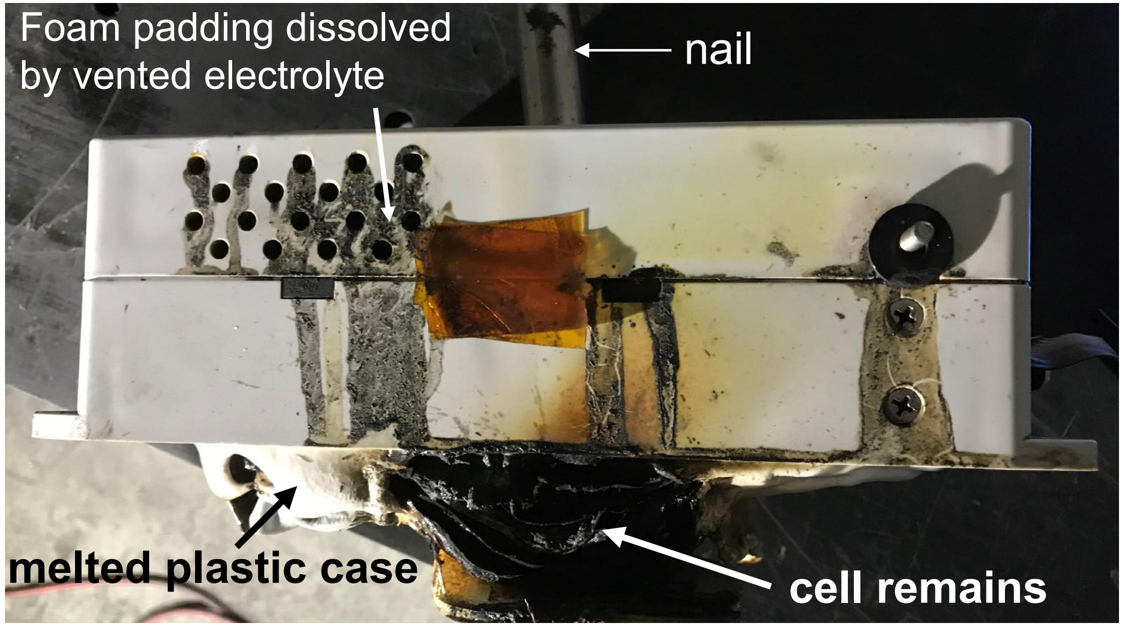


6T Prototype: 3A Charge at -63 °C



CELX-RC modules do not undergo thermal runaway in the most aggressive abuse conditions.

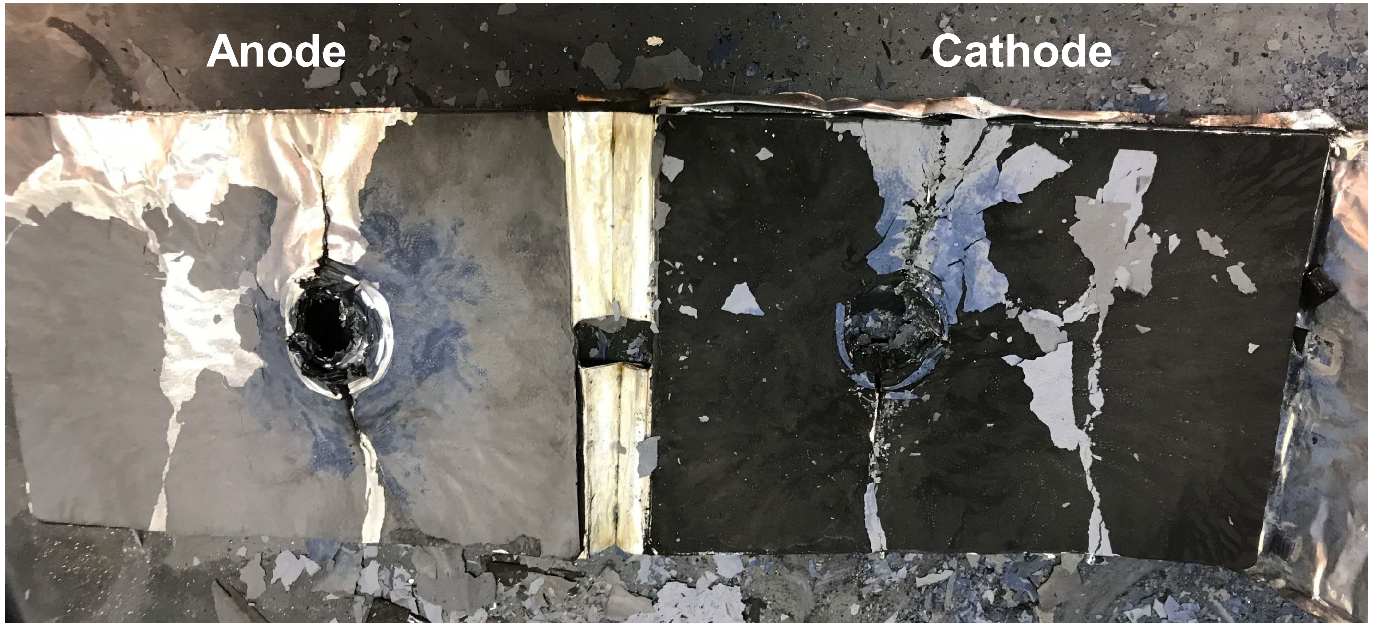
2 cm diam. nail penetration of 200 Wh module



8.5 Ah 11-series-cell module was charged to 28.5 V and through-penetrated with a 2 cm diam. nail per SAE J2464:

- Shorted with temperature reaching ~300 °C
- Significant smoke and electrolyte venting
- No flames or sparks
- SAE J2464 hazard severity level ≤ 4

DPA of cell stack from penetrated module



DPA of shorted cell stack shows electrodes intact with no sign of thermal runaway.

0V-Capable Satellite Battery Cells

Zero-V battery cells enable unique capabilities for US satellites.

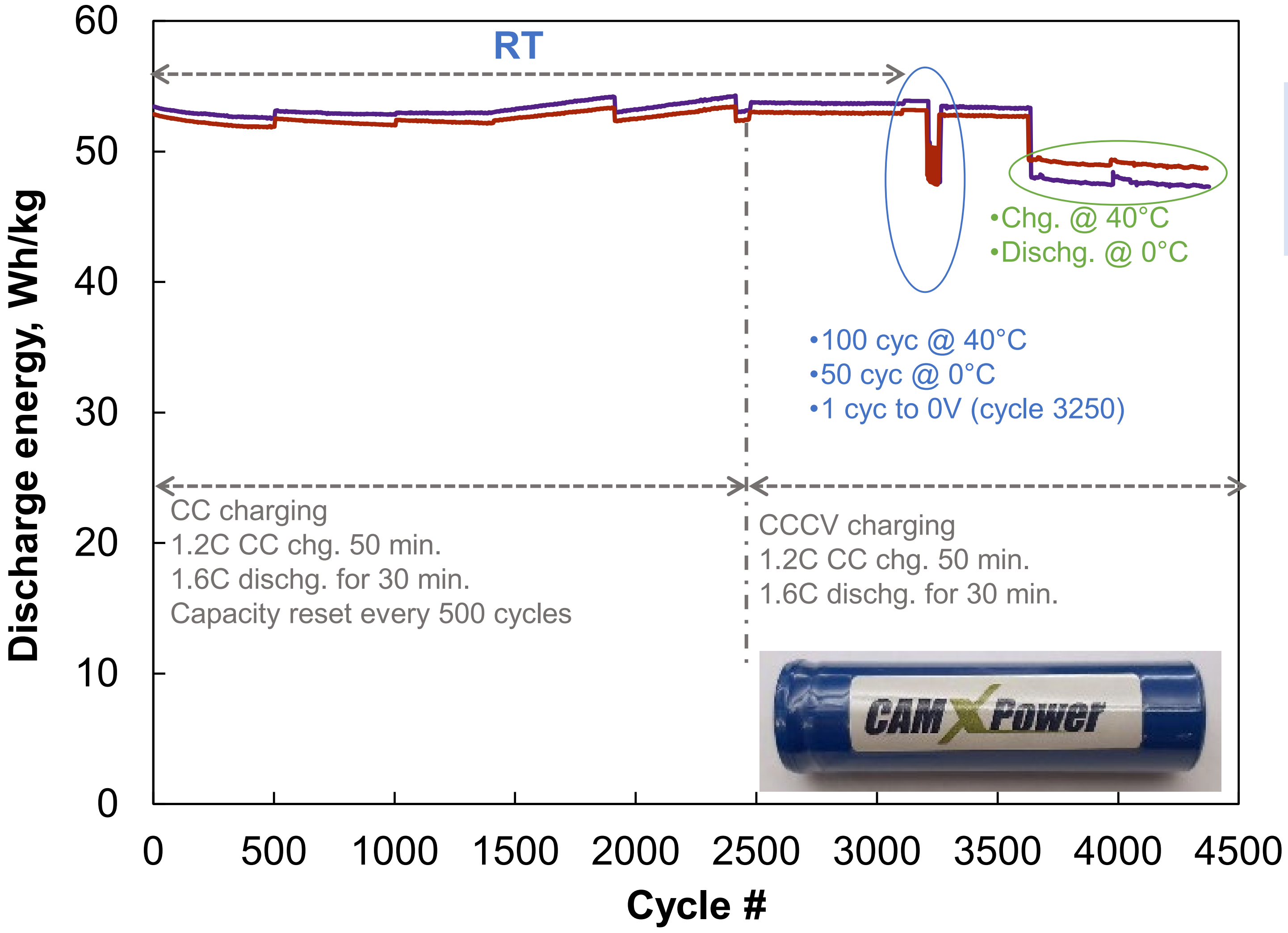
- Satellite batteries that tolerate discharge to 0 V can enable:
  - Reduced satellite battery volume and/or mass,
  - Safe transportation/storage,
  - Recovery from dead-bus failure,
  - Recovery from cyberattack,
  - Hibernation in orbit, allowing satellites to be launched and activated later.
- COTS Li-ion cells can not tolerate discharge to 0 V:
  - Conventional Li-ion anodes employ a copper current collector because it is highly conductive and does not alloy with Li at the low graphite operating voltage (0.1 V vs. Li); however, Cu dissolves during 0 V discharge.
- At present, there is only one supplier of 0V-capable Li-ion cells for use in satellite batteries.
- CAMX Power is pursuing two approaches to 0V-capable Li-ion cells and batteries:
  - LTO-anode cells that use aluminum anode current collector enabled by high voltage of LTO (1.55 V vs. Li).
  - Graphite-anode cells that use alternative non-copper current collector (nC-cc).

CAMX Power has pursued two approaches to 0V-capable cells.

- LTO-anode cells:
  - Lower cell voltage (charging in the 2.4 V – 2.75 V range) is more adaptable to different operating bus voltages and can be readily matched 1-for-1 with series PV cells in low-voltage systems.
  - Exceptional overdischarge and cell reversal tolerance (e.g., -2 V) can enable battery-level discharge to 0 V in absence of management/cell balancing functionality.
  - Limited energy density (up to ~90 Wh/kg), but exceptional cycling stability enables cycling over 70+% of SOC range for ~55 Wh/kg discharge energy in LEO cycling.
  - Implemented in spiral-wound 18650 cylindrical and up to 10Ah prismatic stacked-electrode pouch cells.
- Graphite-anode cells can drop into existing battery designs (3.6 V nominal cell operating voltage):
  - Focused on developing non-copper current collectors (nC-cc) with needed 0V cell discharge stability but with higher conductivity than titanium or stainless steel: 2 materials under study.
  - Conducting 40% SOC range cycling of 18650 cells made in two different designs:
    - Higher electrode loading design providing ~0.8 Ah and ~65 Wh/kg discharge energy in LEO cycling.
    - Lower loading design providing ~0.66 Ah and ~55 Wh/kg discharge energy in LEO cycling.

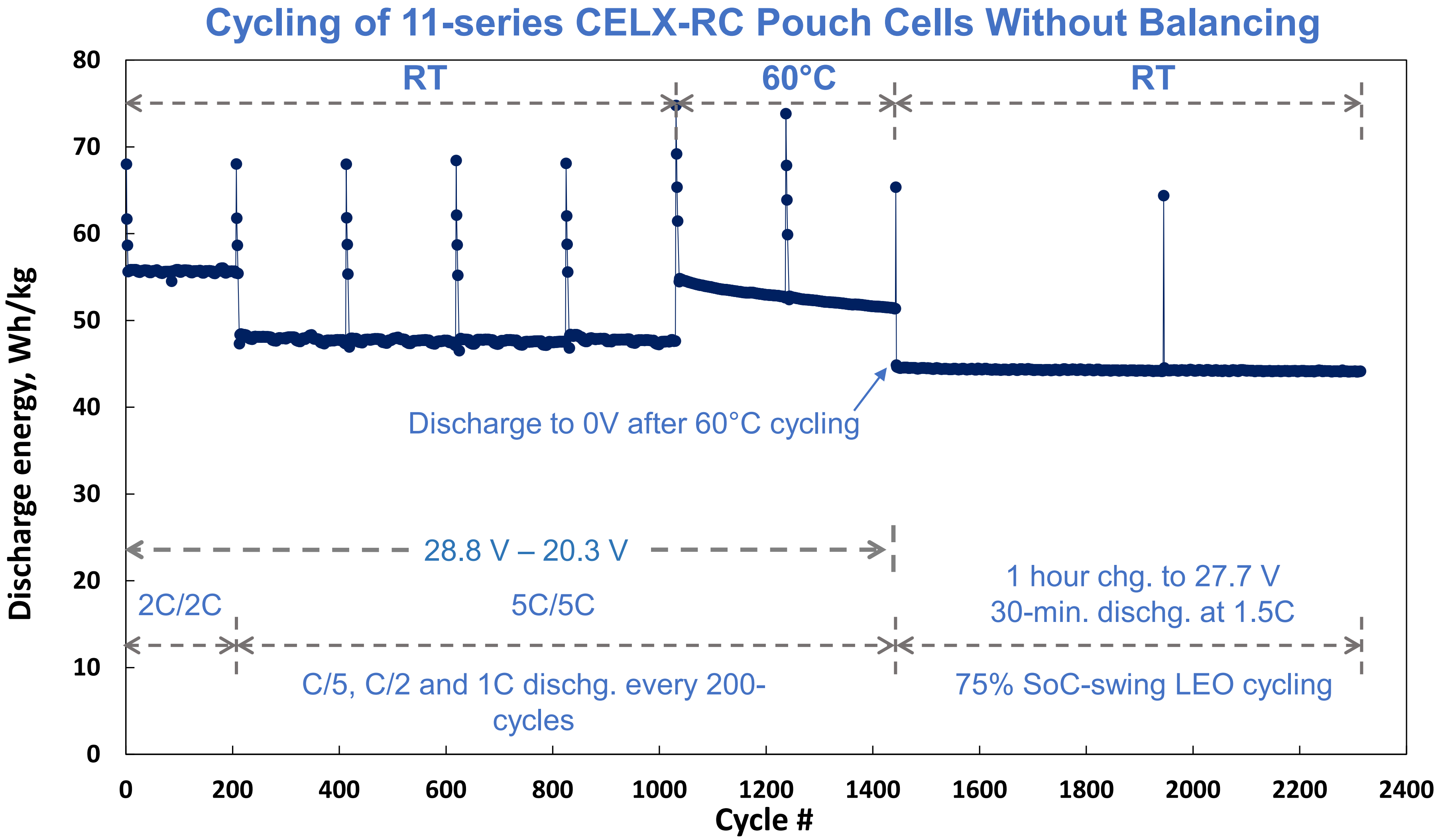
LTO-Anode CELX-RC® Cells

CELX-RC 18650 cells cycle robustly under various LEO-relevant regimes.

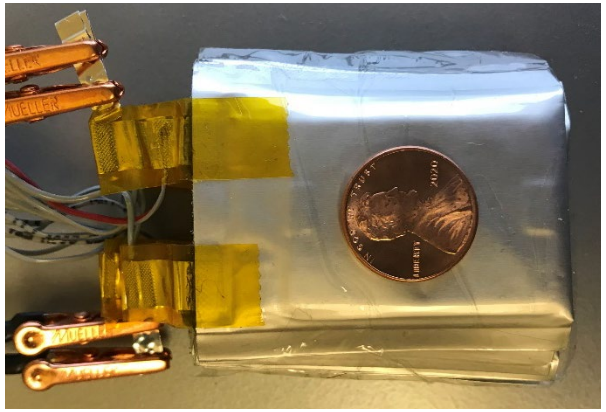


Cycling of two CELX-RC 18650 Cells under Satellite-Relevant Conditions (10 - 90% SoC Range)

We have demonstrated robust cycling of unmanaged, un-fixtured CELX-RC series-cell stack under varied rates and temperatures.

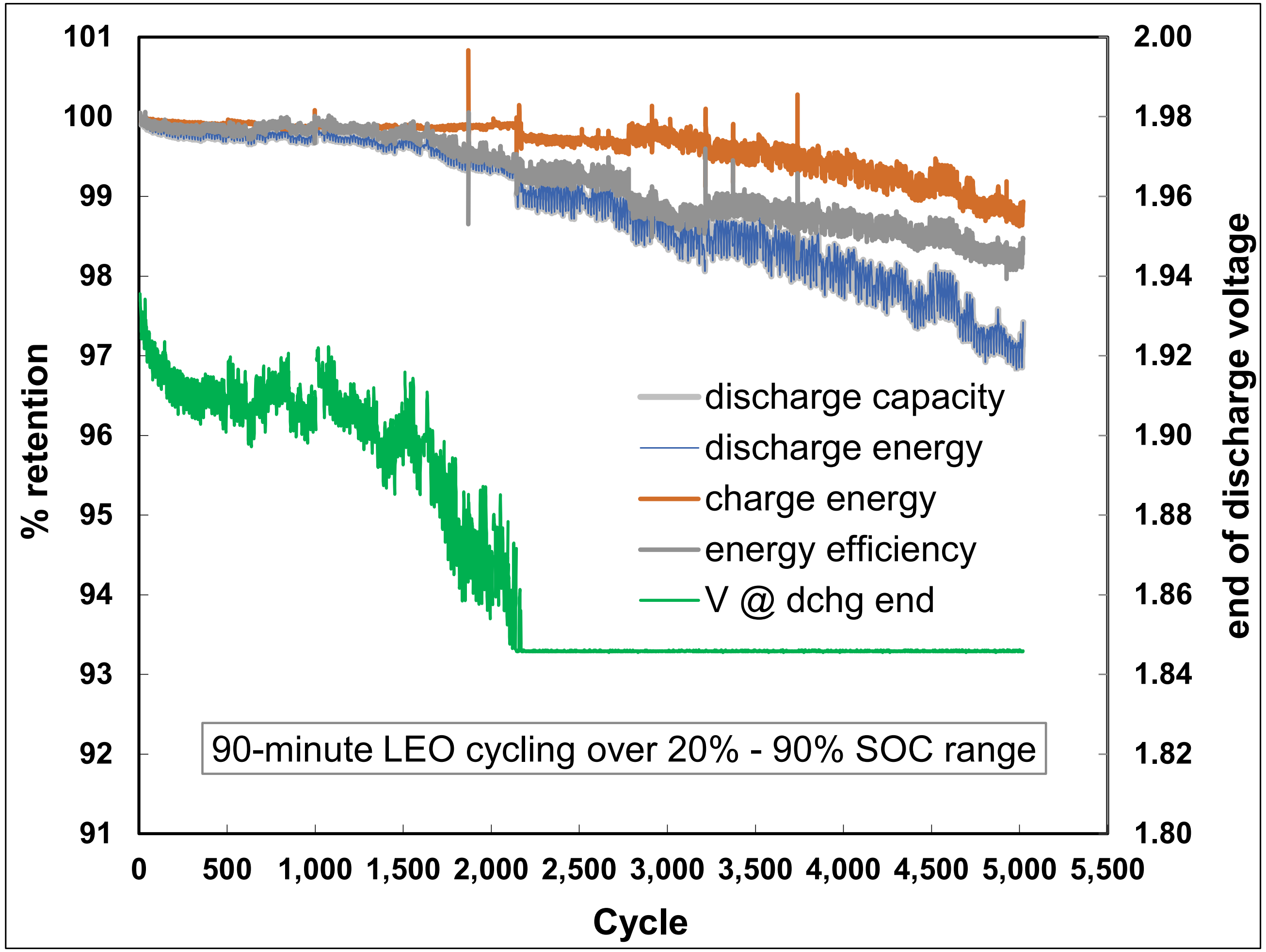


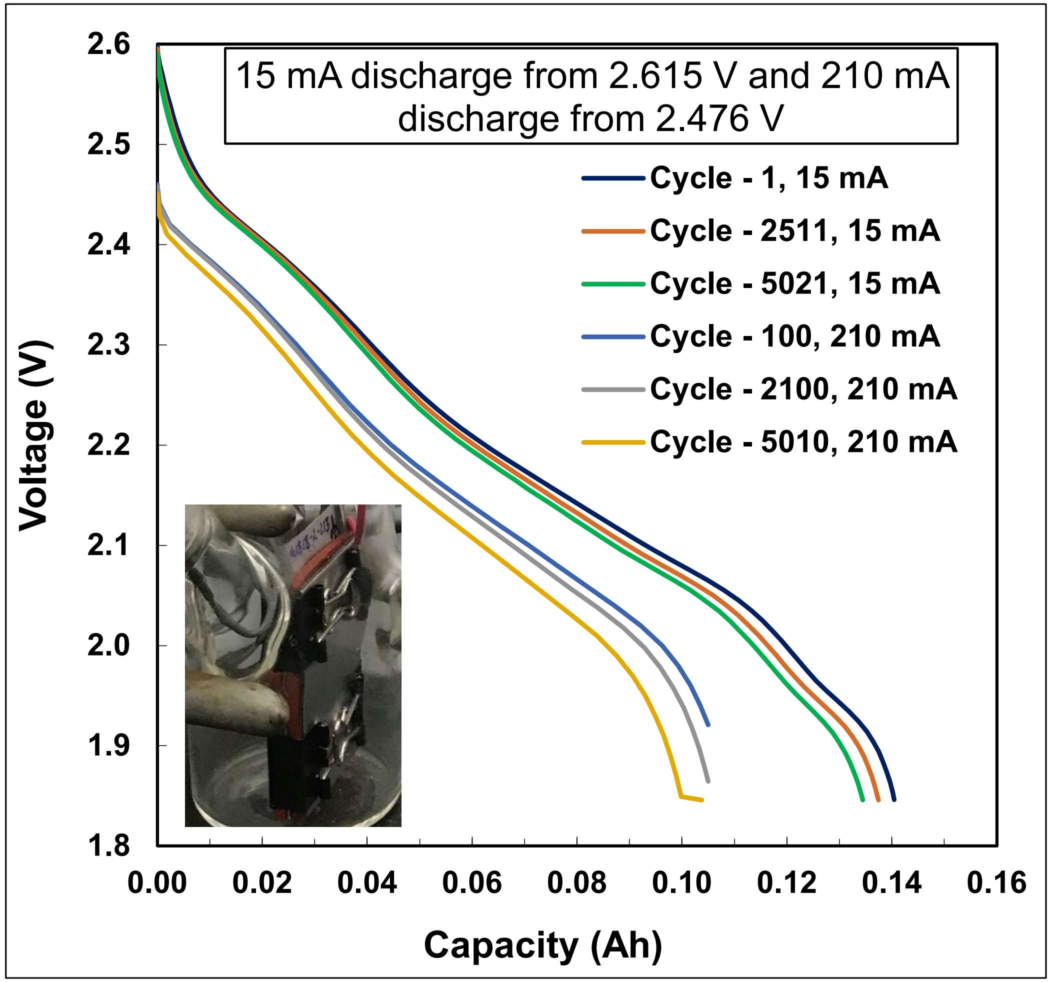
- 11-S pouch cells (160 mAh).
- BoL: 0.3% capacity variance.



CELX-RC pouch cells cycle stably under vacuum with only slight (~7 psi) clamping pressure.

CELX-RC Pouch Cells: 90-minute LEO Cycling over 20% - 90% SOC Range in Vacuum.

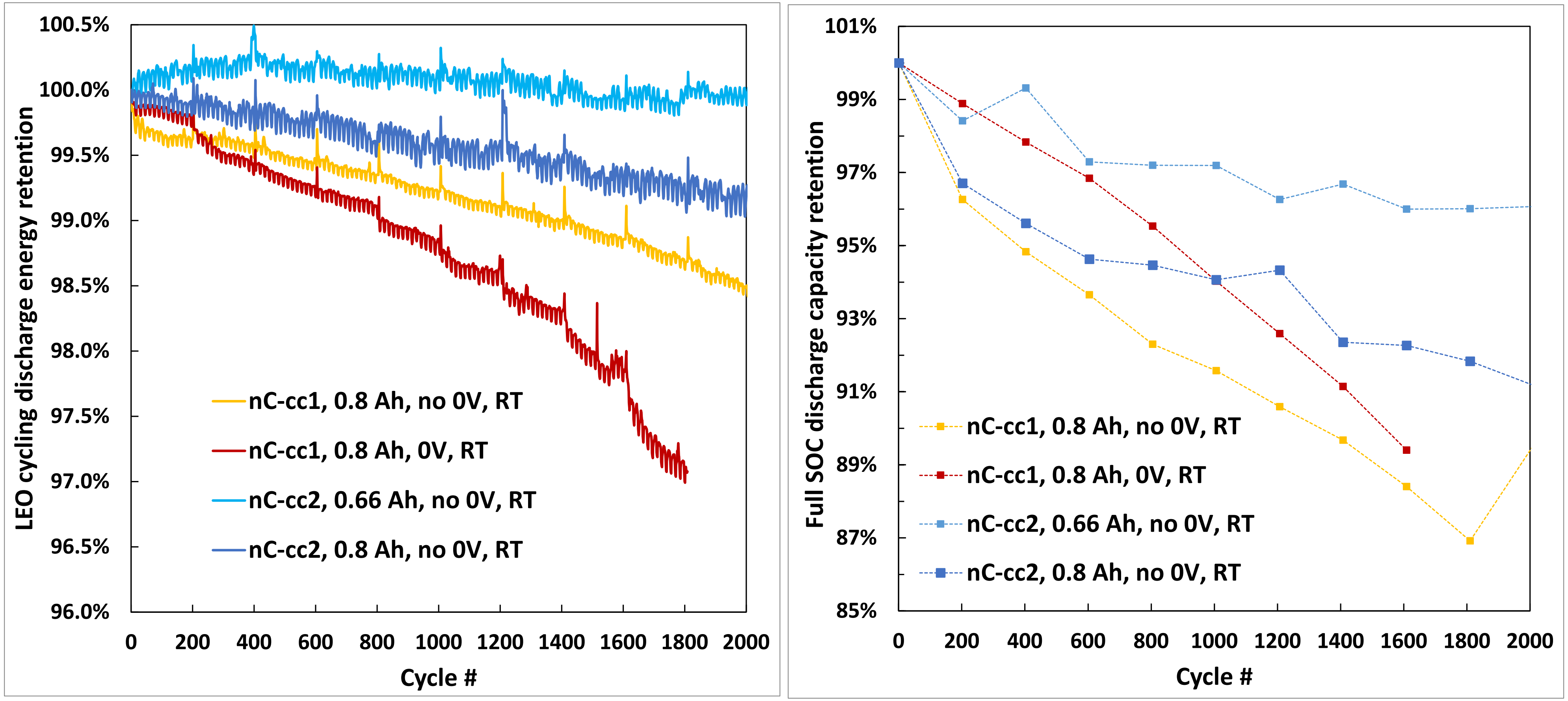




Graphite-Anode Cells

We are investigating different non-copper current collectors for graphite anode 18650 cells. We have identified one material (nC-cc2) that shows reduced fade in RT LEO cycling with discharges to 0V.

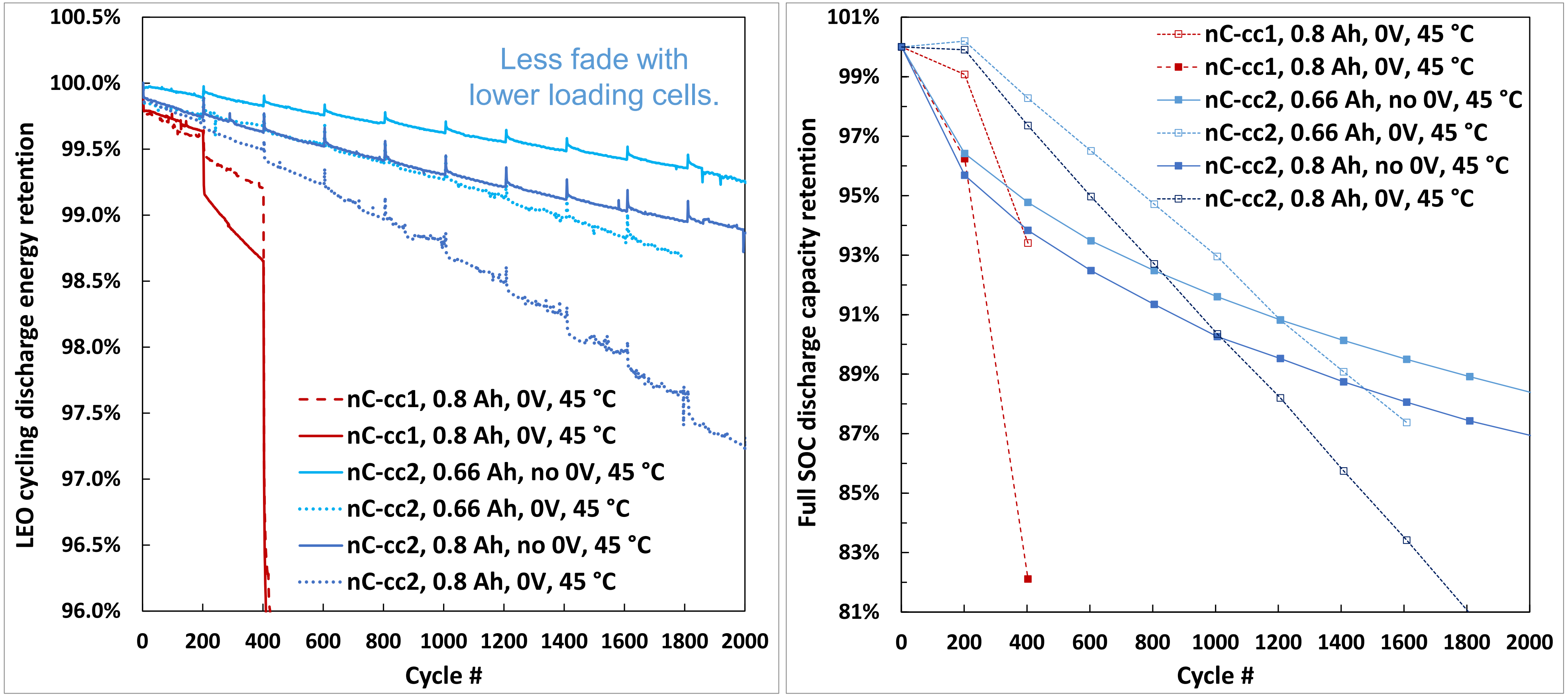
gLNO/Graphite 18650 Zero-V Cells: 90-minute 40% SOC LEO Cycling at RT



- 0.444C CCCV 4.1V, 61 min charge; 0.667C, 35 min discharge
- Every 200 cycles: Full SOC discharge characterization from 4.1V charge, and CCCV to 0V for 120hr where noted.

We also showed that while nC-cc1 cells fail rapidly when discharged to 0V at 45 °C, the nC-cc2 cells continue to perform well after ~2000 LEO cycles & 9 x 5-day 0V CV holds at 45 °C.

gLNO/Graphite 18650 Zero-V Cells: 90-minute 40% SOC LEO Cycling at 45°C



- 0.444C CCCV 4.1V, 61 min charge; 0.667C, 35 min discharge
- Every 200 cycles: Full SOC discharge characterization from 4.1V charge, and CCCV to 0V for 120hr where noted.

DPA of the 18650 cells with graphite anodes and different anode current collectors after 45°C cycling shows that the anode coating delaminates from nC-cc1 but remains intact on nC-cc2.

nC-cc1 cell after 465 cycles at 45 °C with 2 x 5-day 0V holds.

nC-cc2 cell after 1,000 cycles at 45 °C with 5 x 5-day 0V holds.

Conclusions

Cells for 0V-capable satellite batteries are being developed with 2 different Li-ion cell chemistries.

- **LTO-anode 0V-capable cells offer very robust characteristics:**
  - Lower absolute energy density than graphite-anode cells can be mitigated by cycling over broader SOC range (e.g., 70+%).
  - Capability for unmanaged cycling can enhance survivability.
  - Safety/abuse tolerance superior to graphite-anode cells.
  - Adaptable to multiple form factors.
- **Graphite-anode 0V-capable cells can be drop-in replacements in current Li-ion satellite batteries:**
  - Require anode current collector other than copper or aluminum.
  - Current collector with high conductivity is desirable for high power capability.
  - Have higher energy density than LTO-anode cells.
  - LEO cycle life requires cycling over limited SOC range (e.g., 40%). Testing for broader SOC range cycling is ongoing.

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