Self-Discharge Measurements for Cells in Cycling Li-Ion Batteries

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Note: Pictures, Graphs and Diagrams shown on the briefing charts are notional items, not exact.

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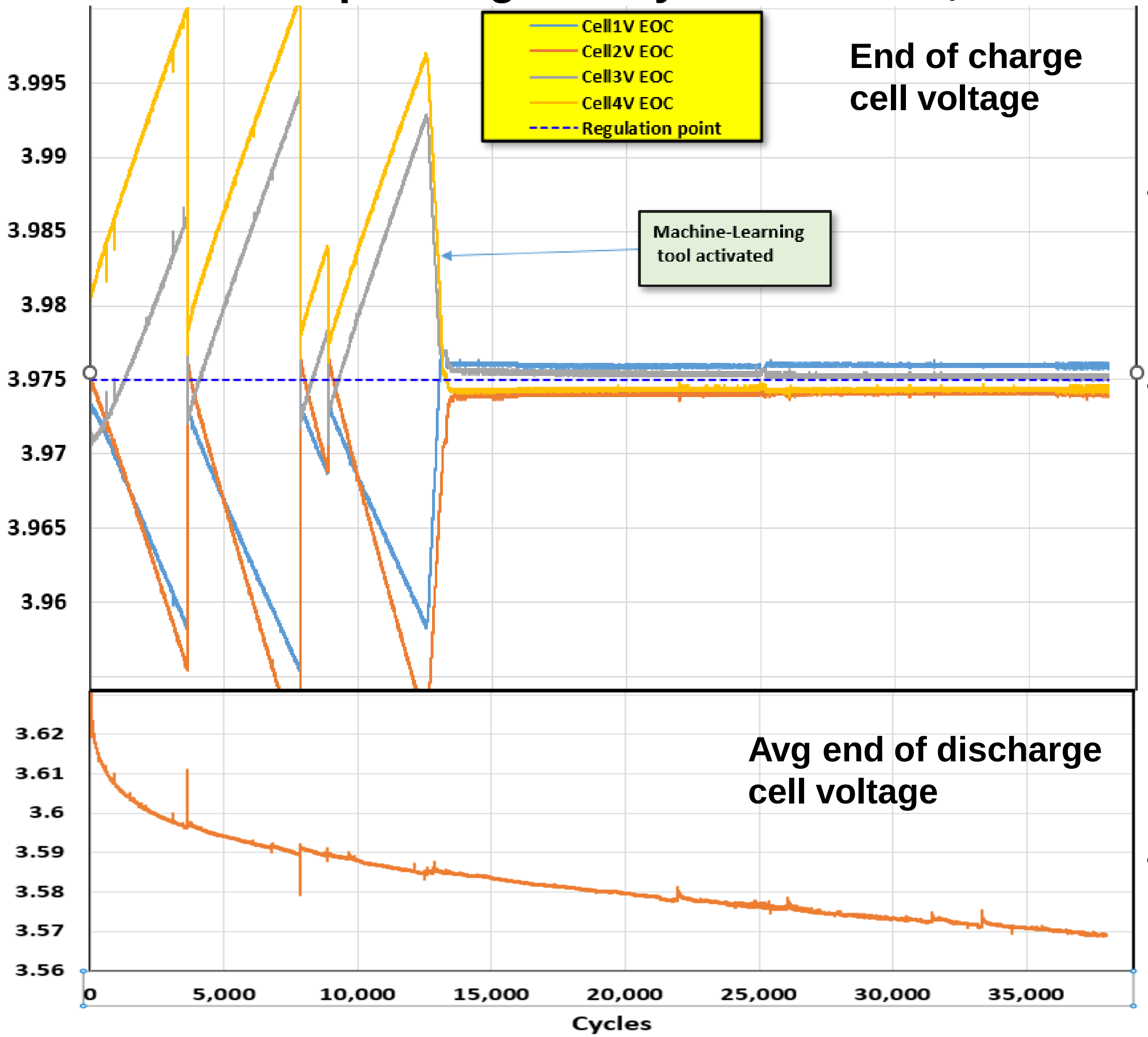
Measurement of Cell Self-Discharge Loss While Li-Ion Batteries are Operating

- **Why do we care about Li-ion self-discharge (typically <C/20,000)?**
  - *Self-discharge can create capacity imbalance between cells in batteries*
  - *Sudden significant changes may signify impending cell problems*
- **Battery charge and discharge operation prevents traditional measurements of open-circuit cell voltage decay rates**
- **We have developed a Machine Learning (ML) tool that continuously monitors cell self-discharge in operating Li-ion batteries**
  - *Can be added to an operating battery control system*
  - *Requires access to cell voltage measurements*
  - *Continuously learns the duty-cycle for switching 10-50 Kohm across each cell to keep cells in each string balanced, which provides the internal cell losses*
- **Data will be shown for four batteries where we recently added ML tool**
  - *Battery 1 (four 12-Ah cells): LEO cycling for 7^{+} years*
  - *Battery 2 (four 7-Ah cells): LEO cycling for 23 years*
  - *Battery 3 (four 40-Ah cells): accelerated GEO cycling after storage for 16 years*
  - *Battery 4 (three 40-Ah cells): LEO cycling for 22 years*

Battery 1: Four 12 Ah Li-Ion Cells

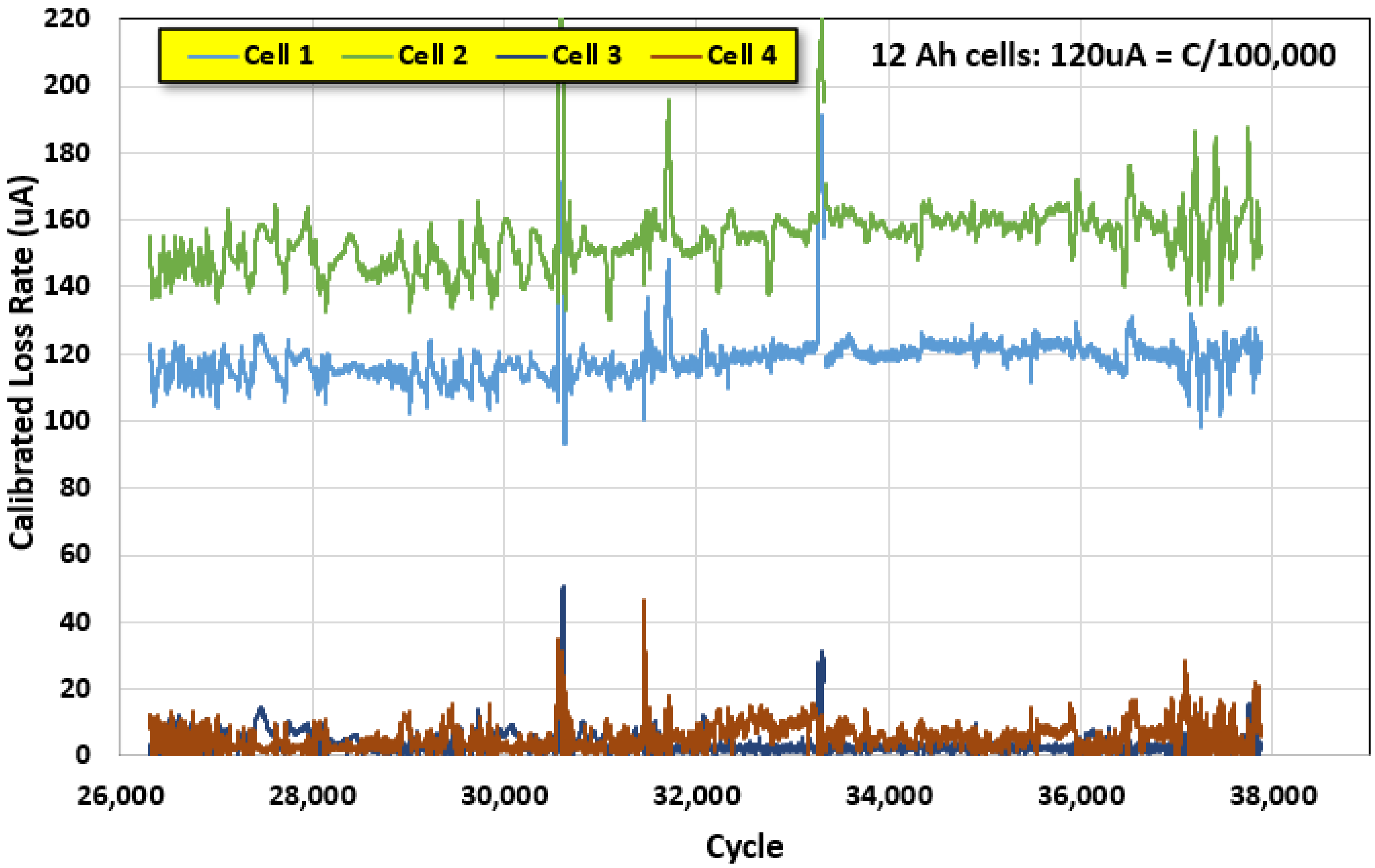
- 7+ Year LEO operating history at 30% DOD, 3.975 V/cell charge voltage



- **Cells periodically manually rebalanced during first ~14,000 cycles**
- **ML tool run after cycle ~14,000 to monitor self-discharge while keeping cells balanced**
- **Essentially no effect on battery discharge voltage performance**

Battery 1 Self-Discharge History

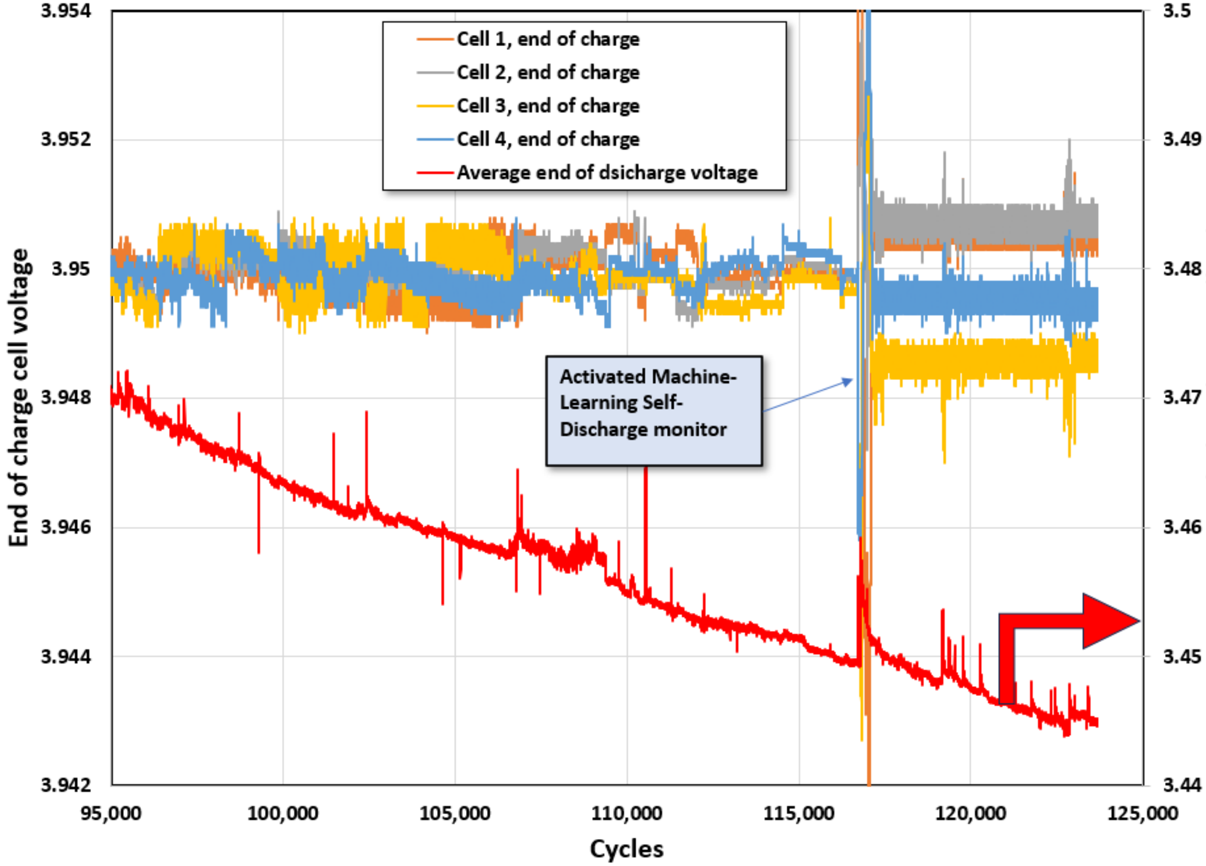
- Self-discharge loss rates generally stable for last 12,000 cycles



- Can fluctuate due to test interruptions or temperature fluctuations
- Cause for recent fluctuations for cell 2 is uncertain

Battery 2: Four-Cell 7Ah Li-Ion Battery

- 23-year LEO cycling history: 124,000 cycles at 20% DOD
- Charged battery to 3.95 V/cell

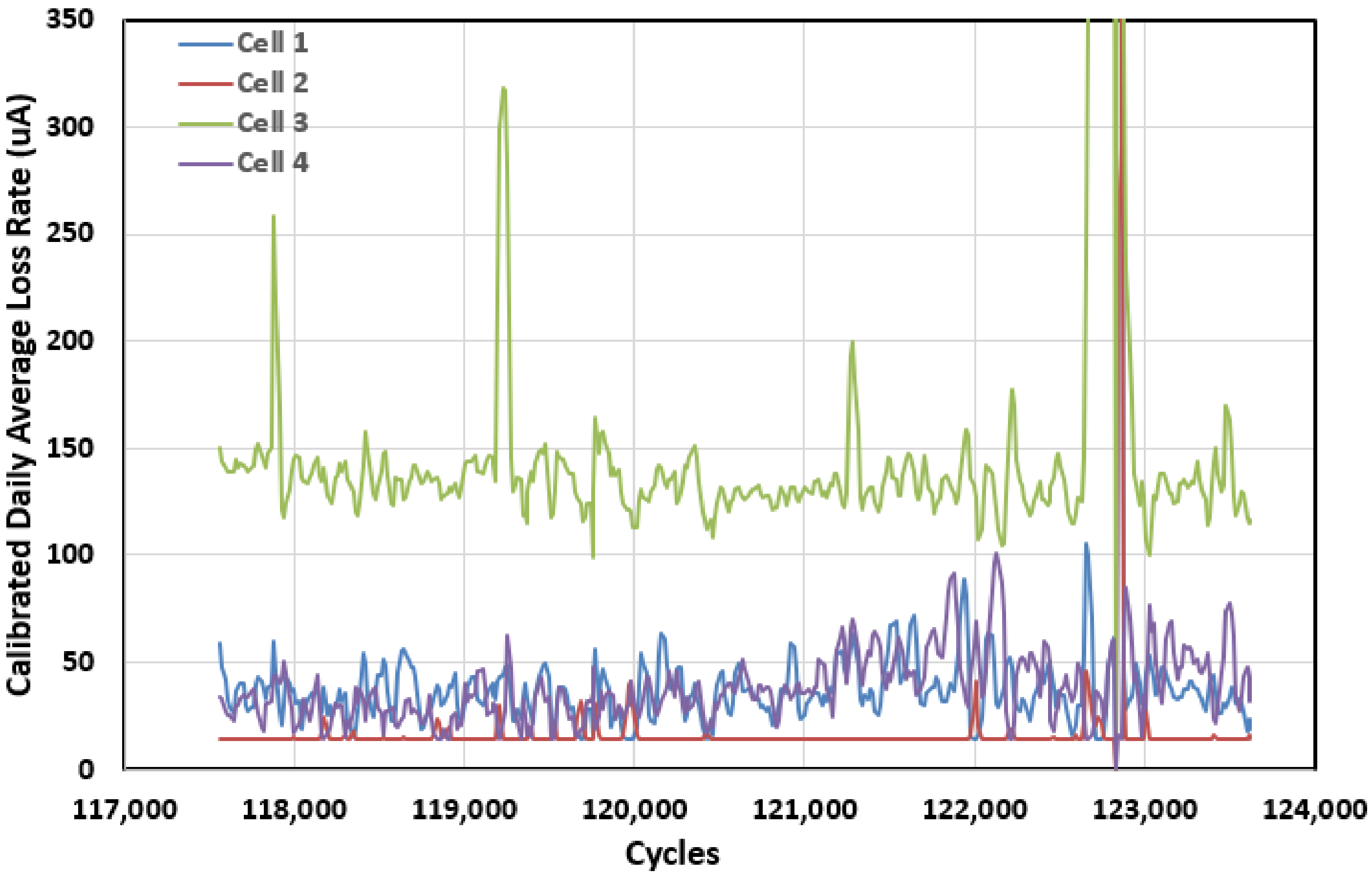


Replaced cell charge voltage regulators with ML tool near cycle 117,000

- Continuing stable cell and battery performance

Battery 2 Self-Discharge History

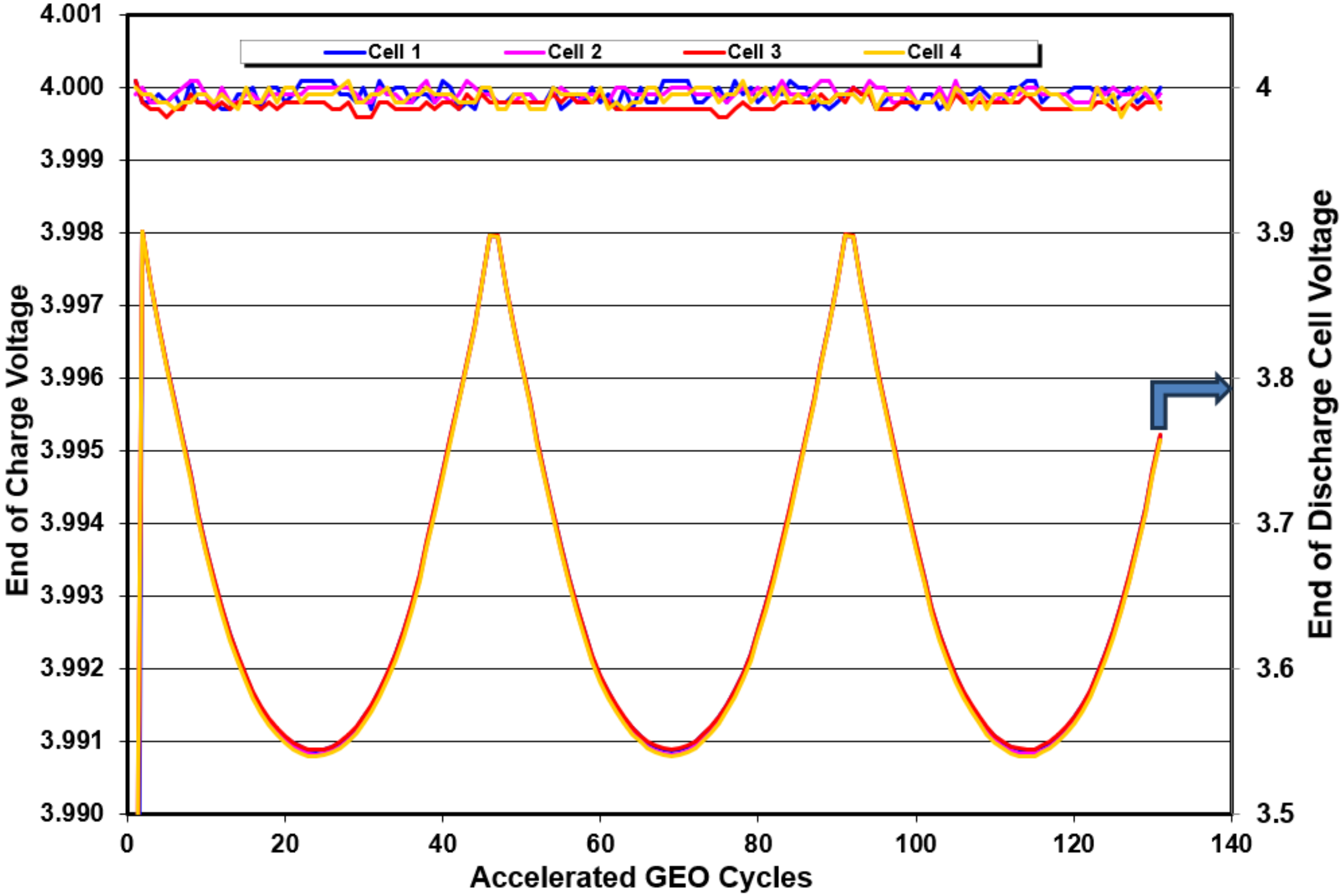
- **Self-discharge loss rates have been stable for last 6,000 cycles**



- **Plotting a daily average takes out effects from daily temperature cycles**
- **Fluctuations sometimes observed when test interruptions occurred**

Battery 3: Four-Cell 40Ah Li-Ion Battery

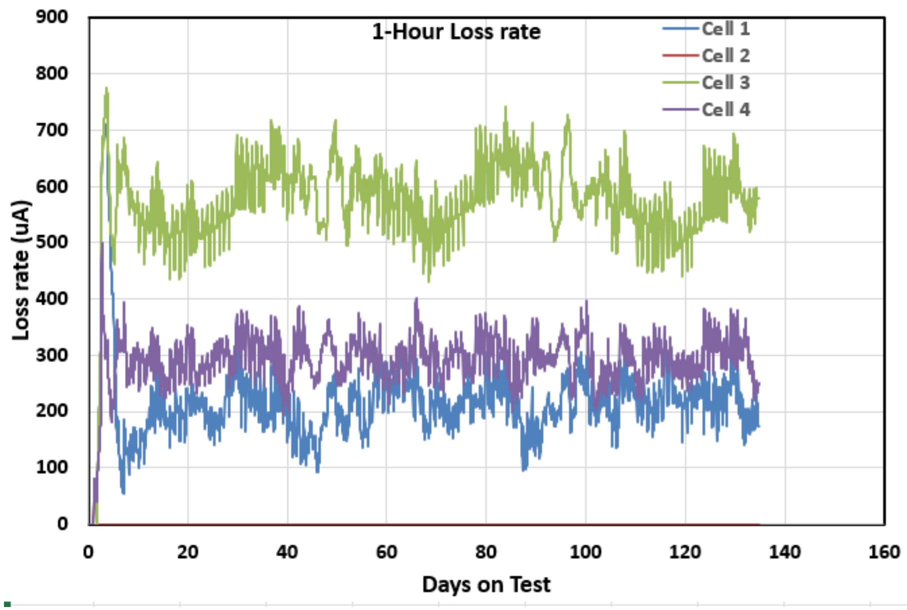
- Accelerated GEO cycling history after 16 years of storage (3 seasons)
- Charge battery to 4.00 V/cell, ML tool for self-discharge monitoring

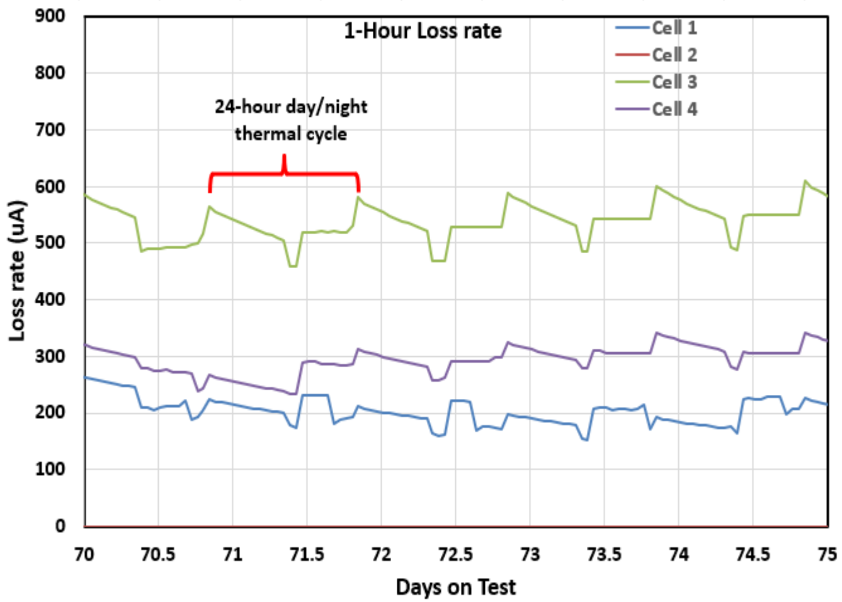


- Keeps cells precisely balanced while monitoring internal losses

Battery 3 Self-Discharge History

- Self-discharge monitored every hour shows 24-hr repeated pattern
- Caused by small (<0.1°C) day/night temperature variation

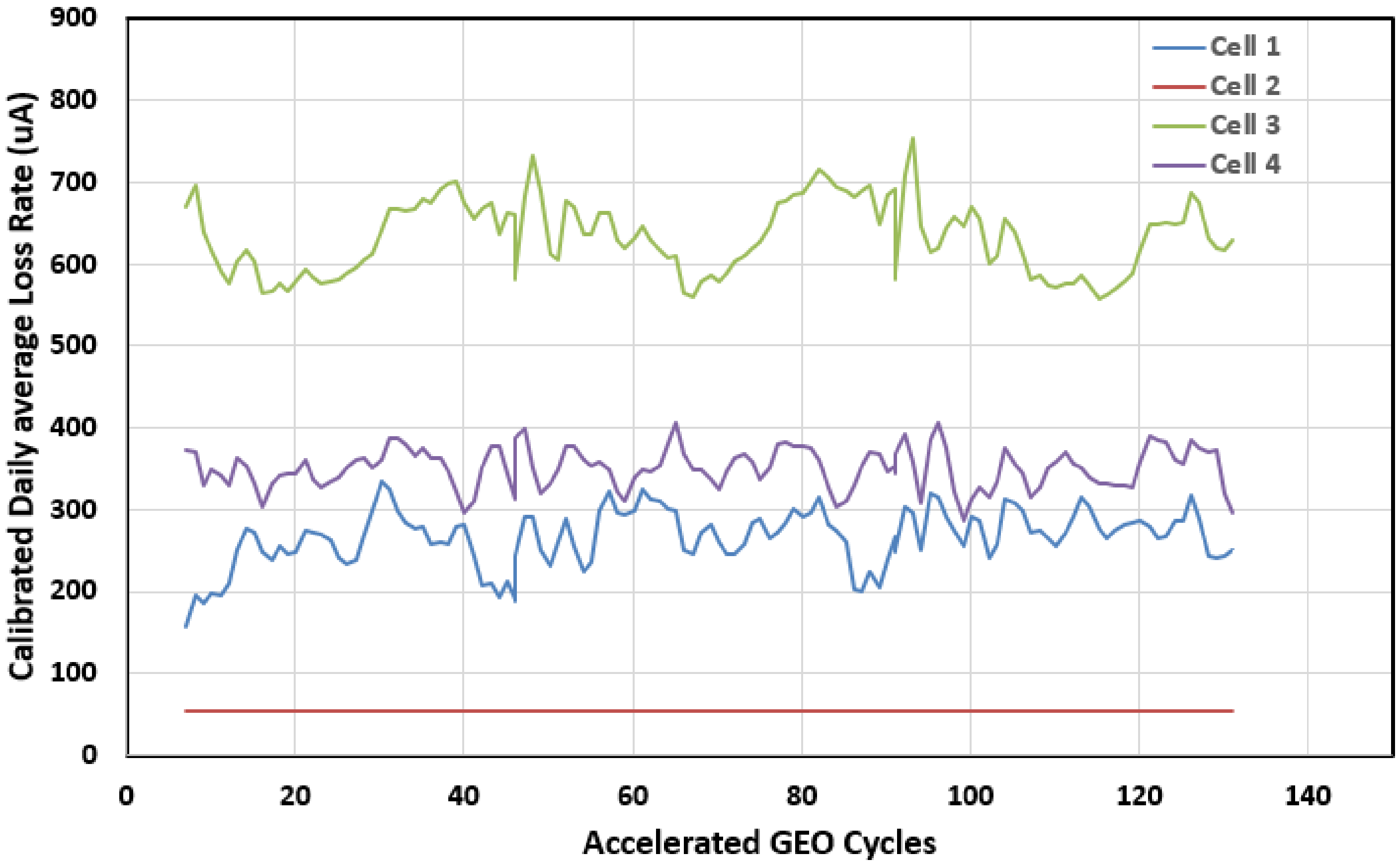




- Apparent internal losses are sensitive to temperature variations
- Day/night temperature effect can be removed by averaging over 24-hr

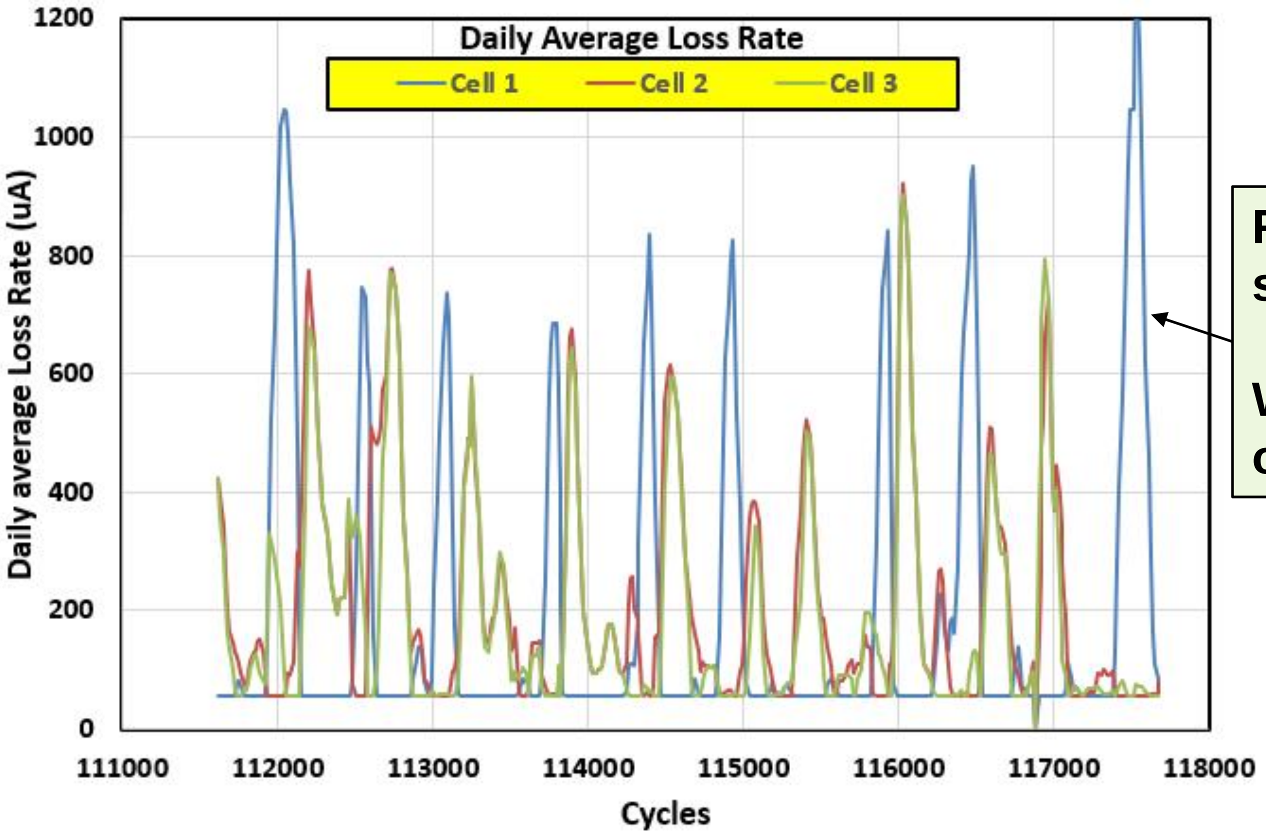
Calibrated Battery 3 Daily Self-Discharge History

- **24-hr averaging removes effect of day/night temperature fluctuation**
- **Cell 3 shows depth-of-discharge fluctuation over 45-cycle season**
  - *Internal cell losses are greatest during periods of low-DOD cycling*
  - *Other cells do not show this fluctuation*



Three-Cell Battery 4 (40 Ah)

- LEO cycling for 22 years at 15-30% DOD (15% for last 6 years)
- Charge to 3.90 V/cell, ML tool self-discharge monitor last 6,000 cycles



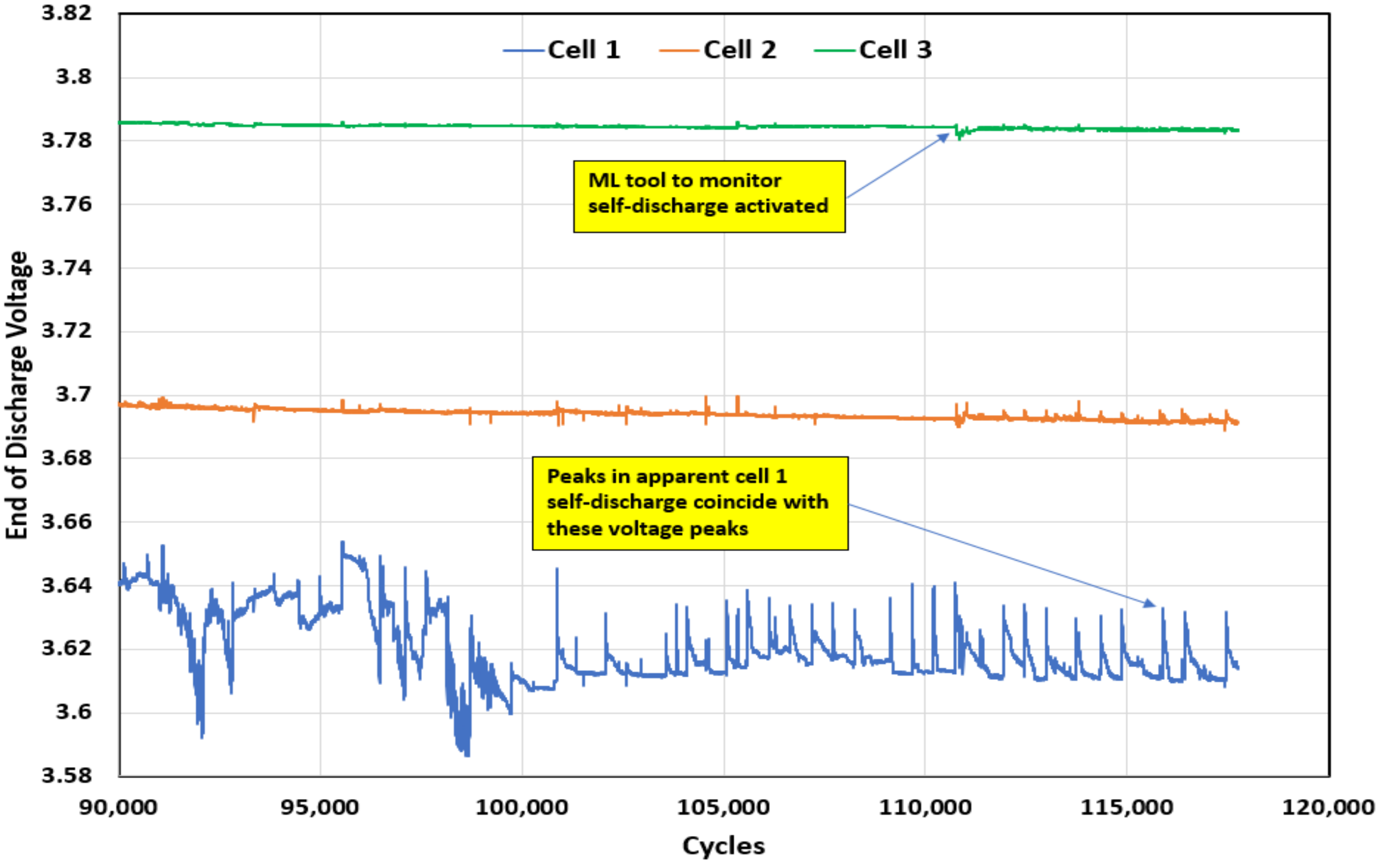
Fluctuations seen for Cell 1

What is going on?

- Internal loses are not stable like other batteries we have trended
- Cell 1 periodically increases, then decreases as ML tool tries to learn

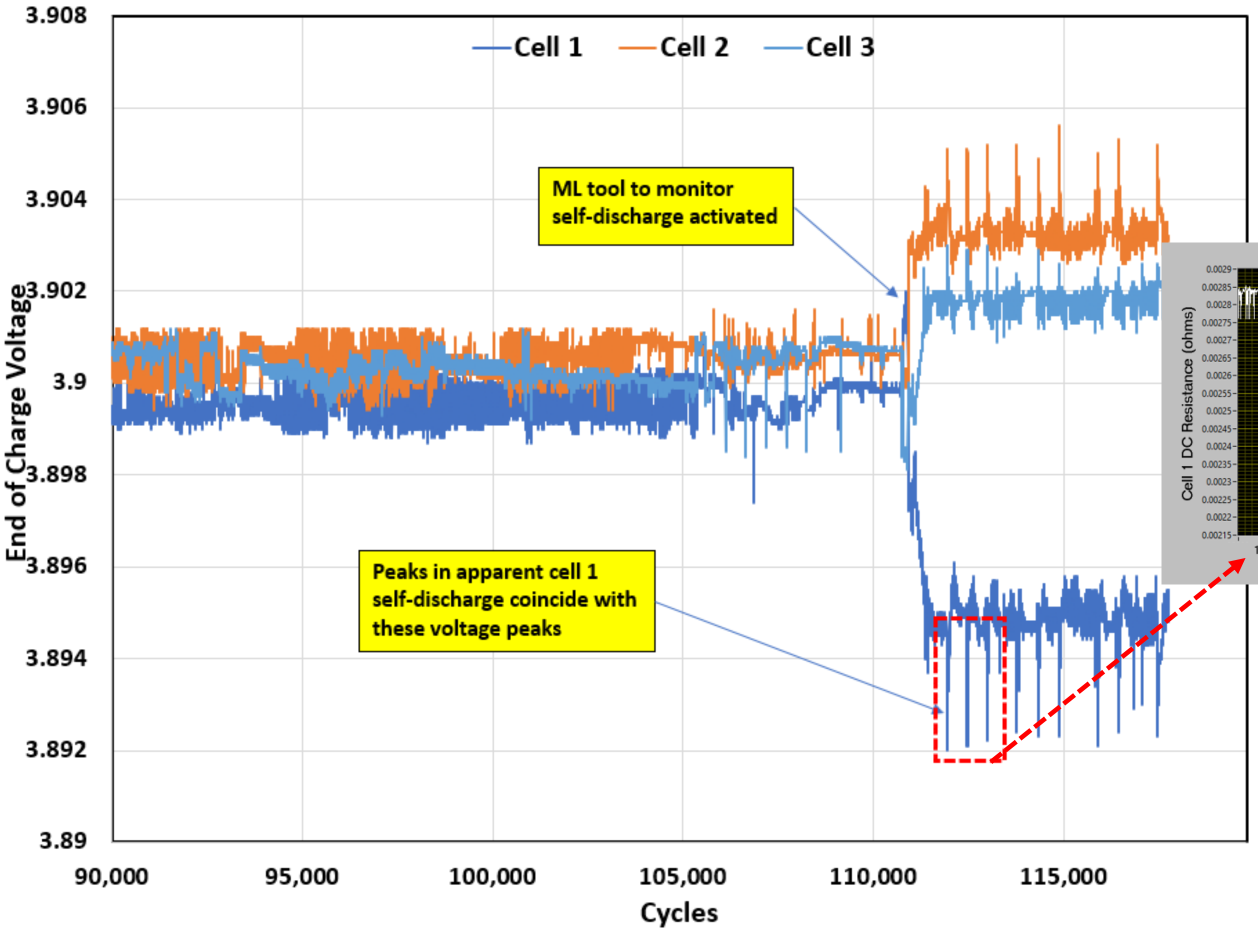
Battery 4: Cell End of Discharge Voltages

- Cell 1 is the most degraded and shows unusual voltage fluctuations
- Voltage fluctuations coincide with peaks in self-discharge detected by ML tool

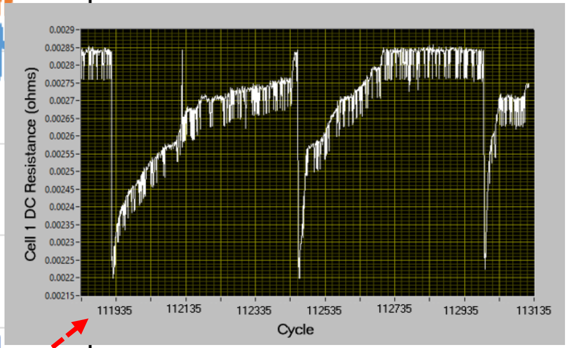


Battery 4: Cell End of Charge Voltages

- **Cell 1 voltage fluctuations caused by DC resistance changes shown**



Voltage fluctuations are interpreted by ML tool as changes in internal cell losses



Cell 1 avg DCR during cycles in red box

- **Cause for resistance changes not known, trending will continue**

Conclusions

- **Machine Learning (ML) can use battery data to learn and monitor apparent internal cell loss rates**
  - *Cell balancing can be a useful by-product*
- **Observed internal cell losses have been observed to be sensitive to parameters other than cell self-discharge**
  - *Cell temperature variations*
  - *Cell resistance changes*
  - *Operating state of charge range*
- **Measurements can be corrected for temperature variations**
- **Sudden changes can warn us of unusual cell behavior in a battery, and perhaps impending end-of-life**
  - *Increasing self-discharge*
  - *Resistance increases or fluctuations*
  - *Variations with state of charge or DOD*
- **Gives us a new tool to trend and better understand battery performance and changes over life**