Cell Performance Signatures during COTS Battery Cycling

Albert H. Zimmerman
The Aerospace Corporation

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

Commercial Off-the-Shelf (COTS) Li-Ion Cells for Space Batteries

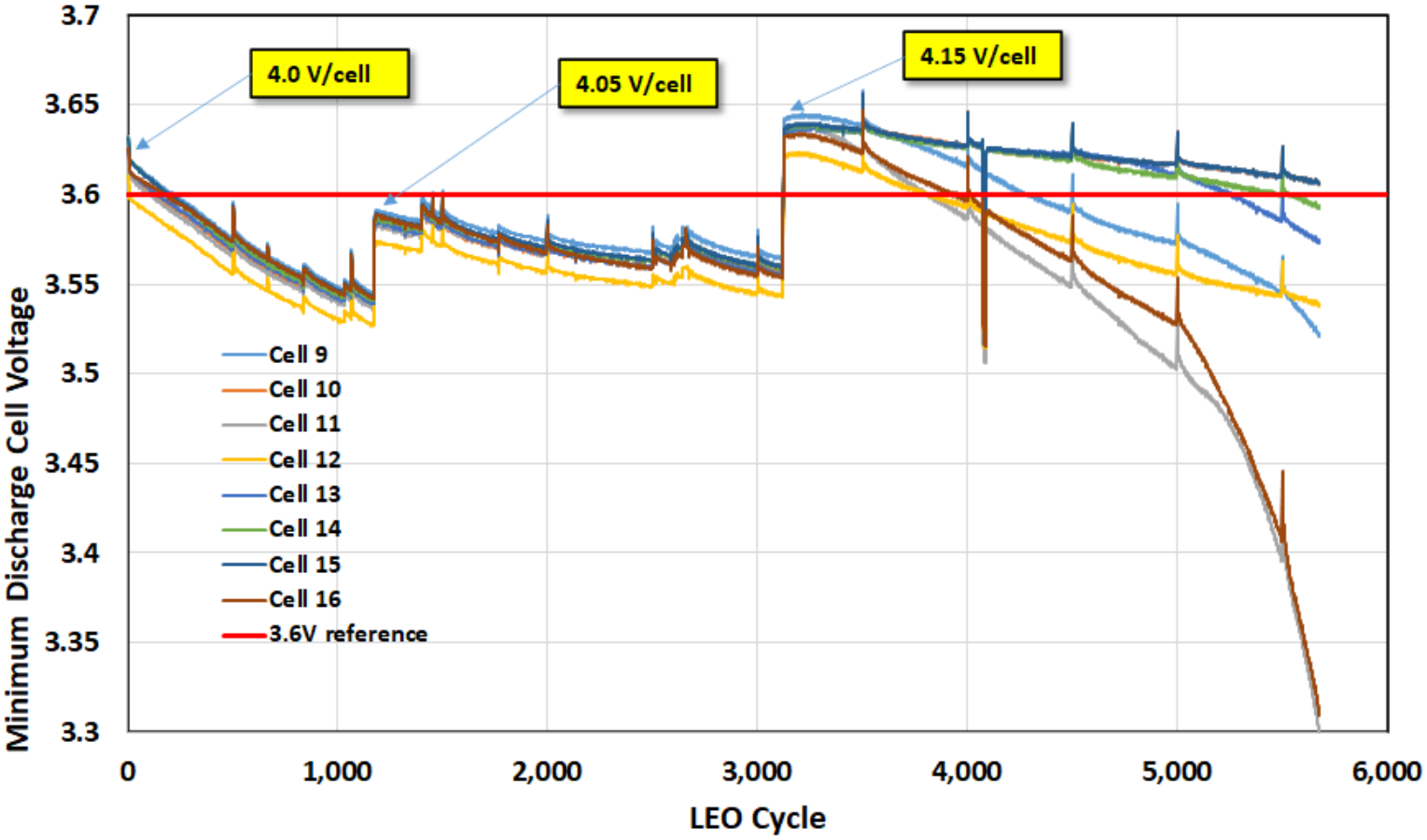
- **COTS cell use has become widespread in space batteries**
  - ***Often in CubeSats or SmallSats where life expectations are low***
- **Failure modes, wear-out trends, and statistics determine battery reliability and life**
- **What are the failure modes for various types of COTS batteries?**
- **Do COTS batteries differ from batteries made with space-type cells?**
  - *Space-type cells show typical wear-out statistical distributions as they age*
- **We have cycled batteries made from six different types of 18650 COTS cells commonly used in space systems**
  - *All six types of cells in 25-30% DOD LEO profiles*
  - *Two types of cells in 38-42% DOD accelerated GEO profiles*
  - *One type of cell in 60% DOD accelerated GEO profiles*
- **A range of observed degradation signatures will be shown**
- **Conclusions**

Battery Design, Cell Matching and Management

- **Batteries consist of 8-cells strings, with one to three strings in parallel**
- **Cells for each battery precisely balanced and matched at beginning-of-life based on capacity, resistance, and self-discharge rates**
- **No cell balancing once cycling was begun**
- **All tests run with battery on a 20°C baseplate**
  - *Temperature gradients in a battery typically less than 5°C during cycling*
- **Peak recharge voltages varied from 4.0 to 4.2 volts per cell**
- **Cells typically saw 1-2 years of storage life prior to cycling**
  - *Storage was typically at 30-50% state of charge*
- **LEO cycling profile of 15 cycles per day (0.29-0.33C peak charge rate)**
- **GEO 45-day eclipse season profile with one cycle per day (72-minute maximum eclipse duration, C/20 peak charge rate)**
  - *Accelerated by shortening solstice period to 2 days*
  - *Capacity discharges between eclipse seasons*

LEO Degradation at Low Recharge Voltages

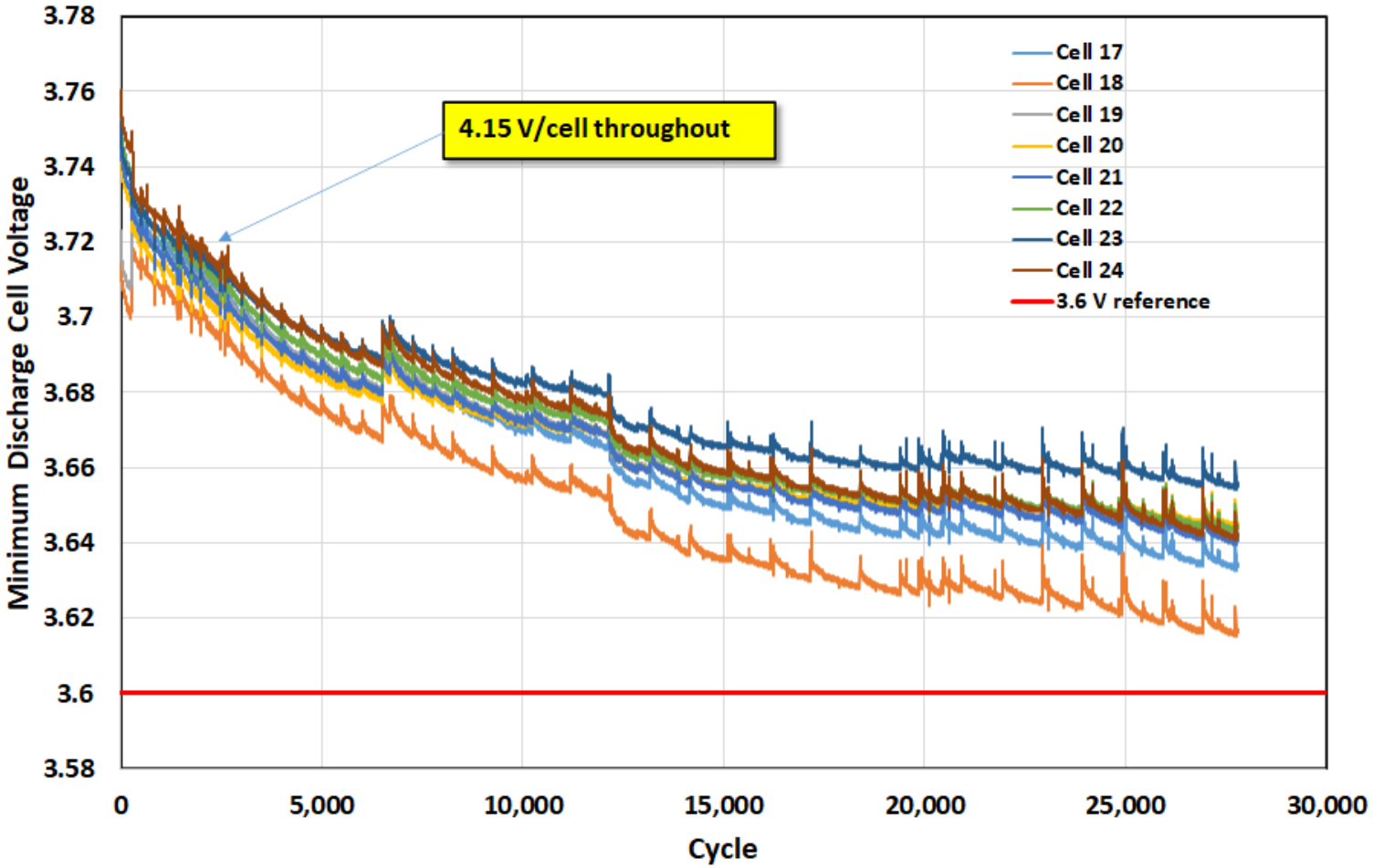
- **Type B 8S1P battery at 29% DOD, started at 4.0 V/cell, increased in stages to 4.15 V/cell, failed after 5,700 LEO cycles**



Did cells degrade faster and fail because we raised the peak charge voltage to 4.15V?

LEO Performance at Higher Recharge Voltages

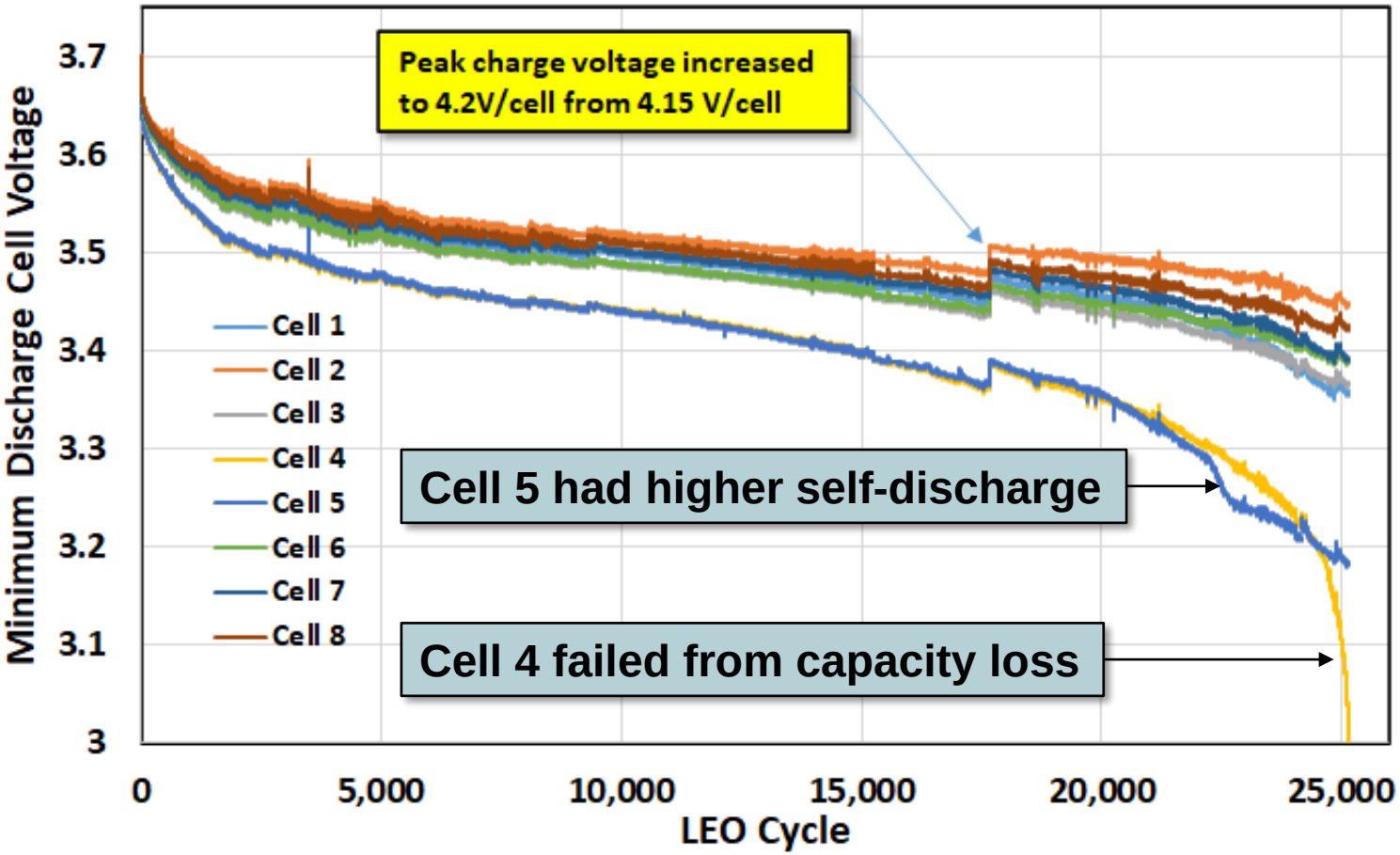
- **Type B 8S1P battery at 27% DOD, started at 4.15 V/cell, stable performance for nearly 28,000 LEO cycles (over 5 years and continuing)**



Five years or longer life is good for COTS batteries

LEO Performance at Higher Recharge Voltages

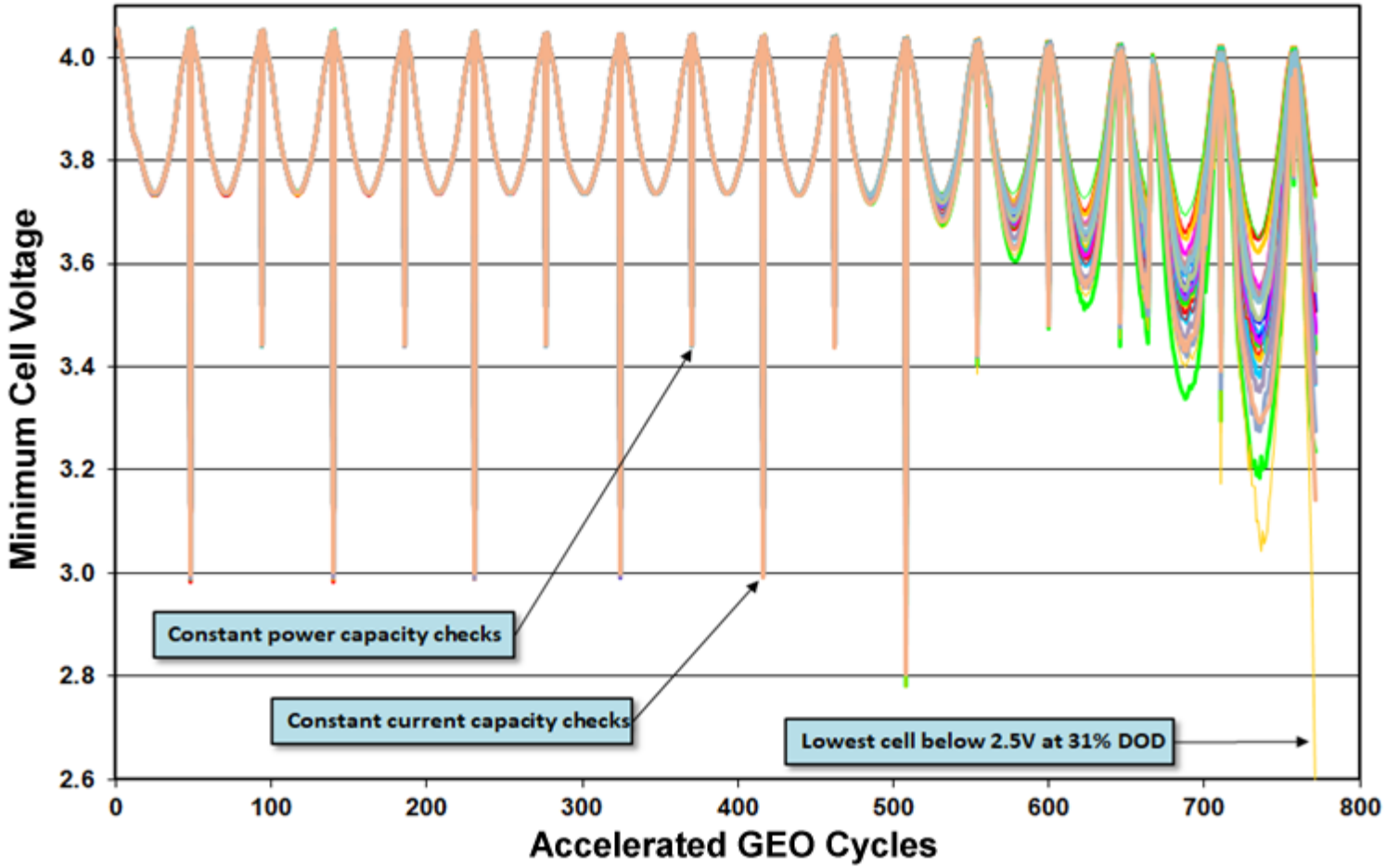
- **Type A 8S1P battery at 25% DOD, started at 4.15 V/cell, increased to 4.2 V/cell due to low voltage in two cells. Nearly made a 5-year life.**



Possible defects in two cells. One with higher capacity loss, other with higher self-discharge.

Degradation in GEO with High Recharge Voltages

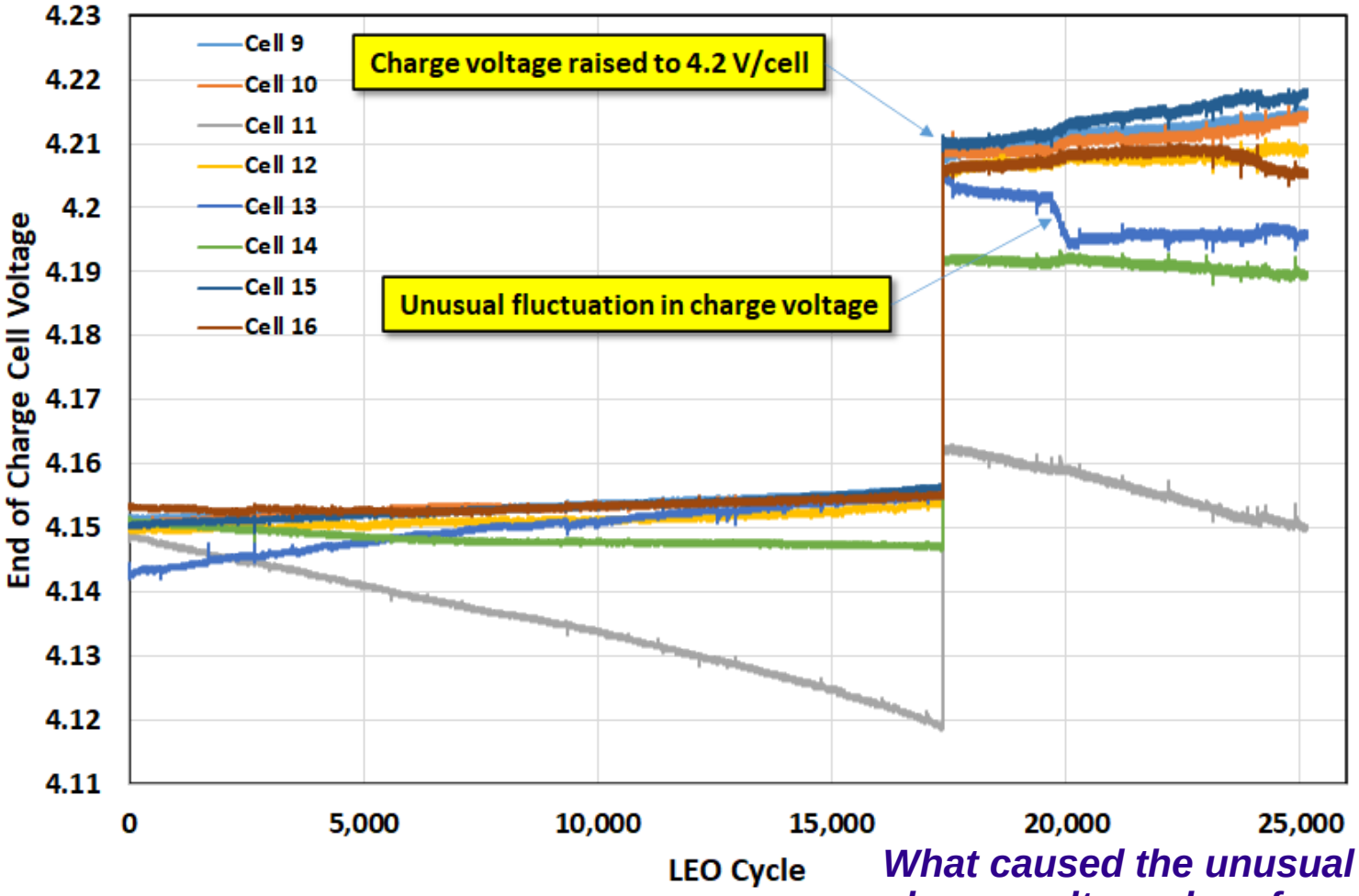
- **Type C 24-cell 8S3P battery at 38% max GEO DOD, 4.2 V/cell max charge voltage, failed from capacity loss in lowest cell after 2.3 years**



All cells show accelerated capacity loss after ~1.5 years

State of Charge Imbalance (high self-discharge)

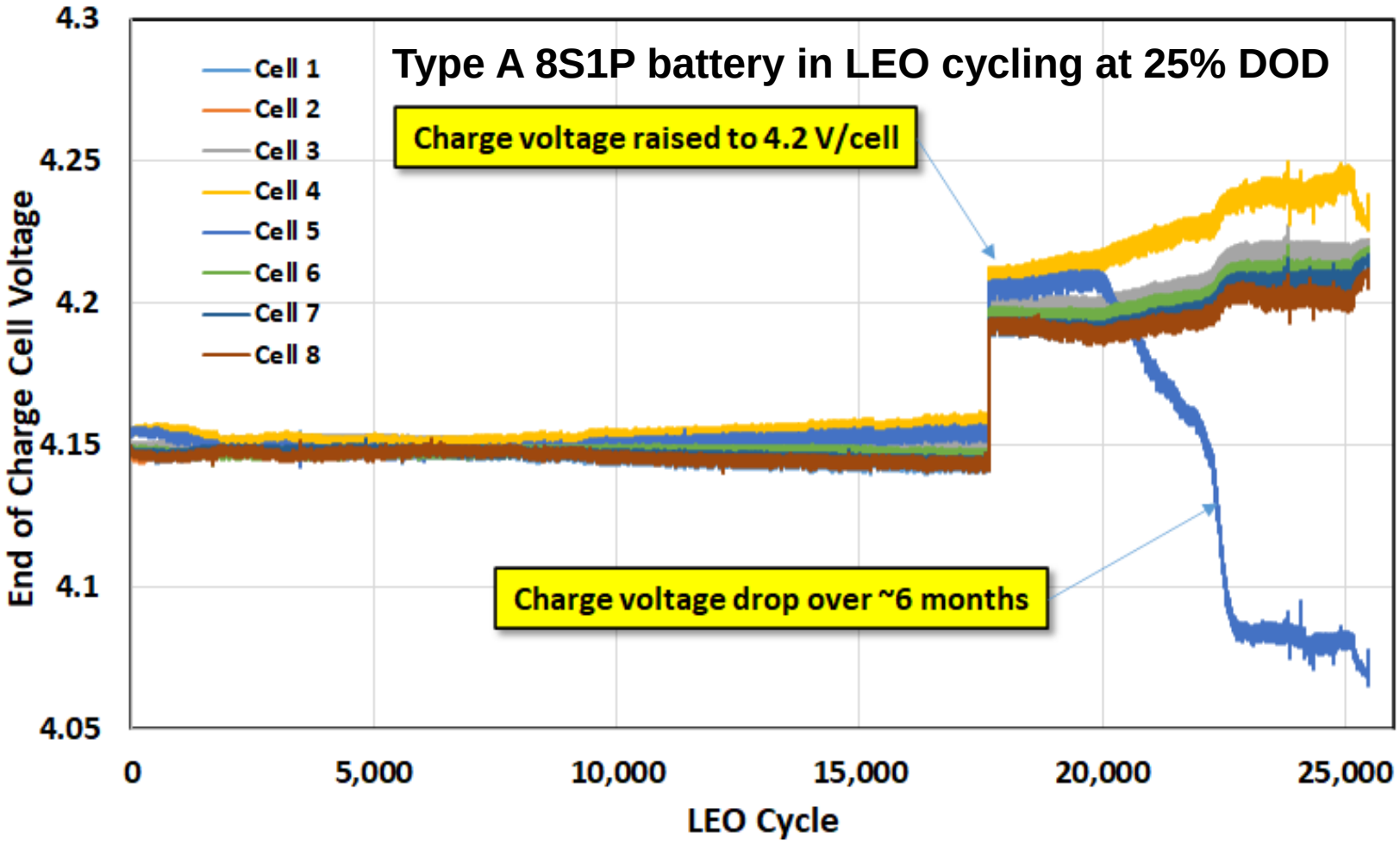
- **Self-discharge caused low end-of-charge voltage divergence for cell 11 in Type C 8S1P battery in LEO cycling at 25% DOD**



What caused the unusual charge voltage drop for cell 13?

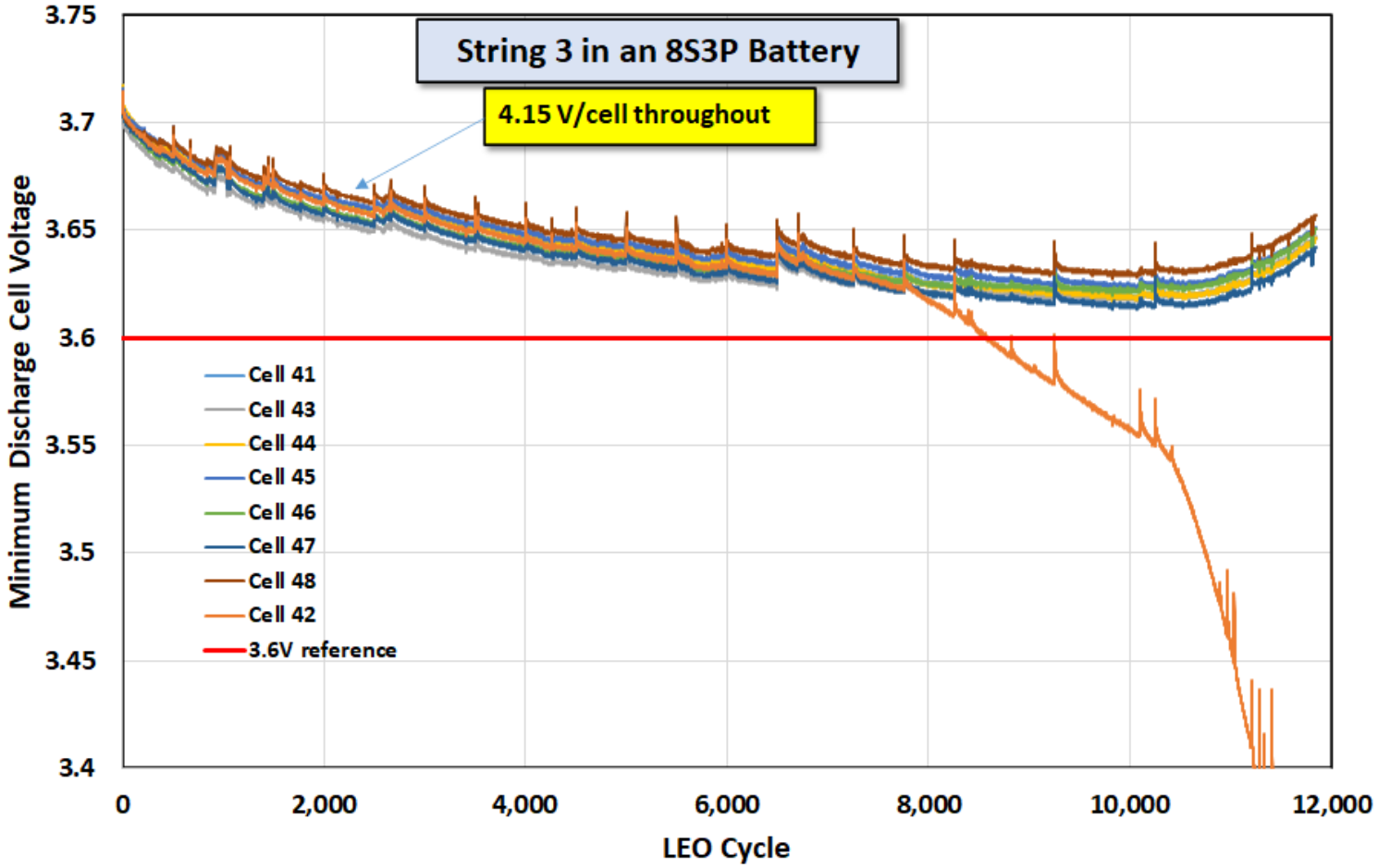
Imbalance Fluctuations

- May be caused by parasitic shorts from Li metal plating
- Tends to go away after the affected cell voltage drops sufficiently



Anomalous Capacity Loss or Resistance Increase

- **Type B 8S1P battery at 29% DOD, anomalous capacity loss in one cell started after ~8,000 LEO cycles**



Possible latent defect in the one cell. Undetectable early in life!

Conclusions

- **Cycle life of COTS batteries can be sensitive to charge voltage level, either too high or too low can reduce life significantly.**
- **Lower DOD can mean more time spent at peak voltage level.**
  - *Can result in increased degradation rates*
  - *Particularly for GEO, where more time spent near full charge*
- **Cell charge imbalance can reduce life, particularly at the highest voltages where Li plating may be more likely.**
- **Cell resistance increase is typically associated with capacity loss, which is the most frequently observed life limiting factor.**
- **COTS battery performance is often controlled by only one or two out-of-family cells.**
  - *The defects causing out-of-family behavior are not readily detected near beginning of life through characterization and matching.*
- **Optimizing the life of COTS batteries can be challenging.**
  - *Testing and appropriate design redundancy recommended to get needed life*