Degradation Trajectory Analysis (DETRAN) for Accelerated Life Prediction of Li-Ion Batteries

Albert H. Zimmerman
The Aerospace Corporation

18-19 November 2020
2020 NASA Aerospace Battery Workshop
Workshop Site

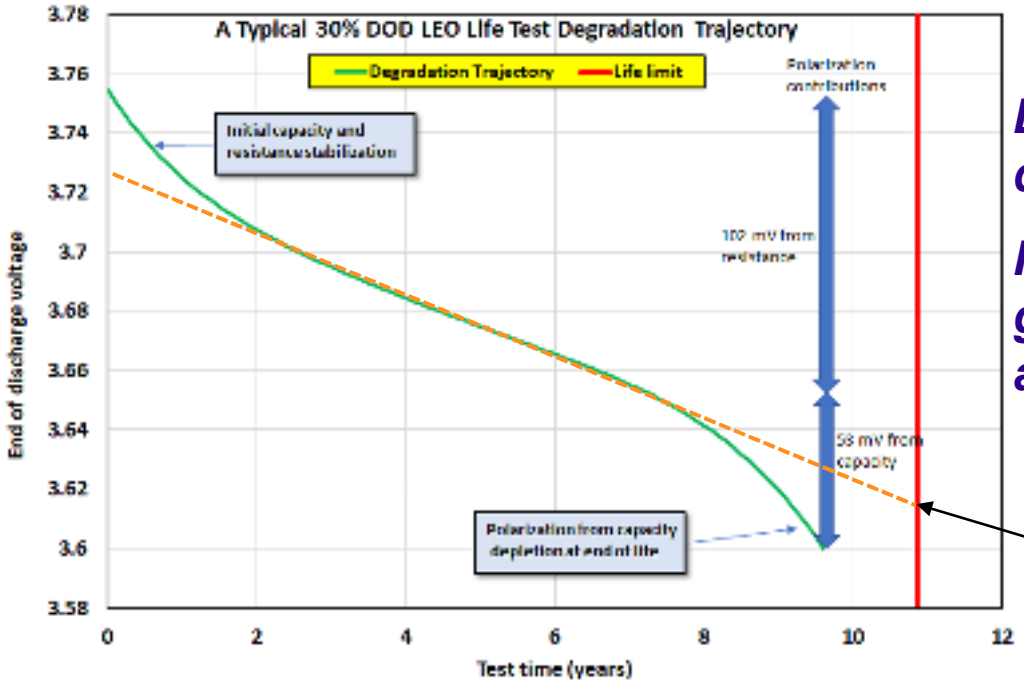
Accelerated Life Testing of Li-Ion Cells

- **Real time life tests can take very long**
  - *Programs need answers much more rapidly to be useful (within ~several years)*
- **We therefore run accelerated life tests to understand degradation faster**
  - *Various acceleration methods have been used*
    - LEO: increase stress with higher DOD (40% vs. 30%)
    - GEO: remove 5-month solstice period (3.75x cycles per year)
    - MEO: shorten cycle time (6-hr cycle vs. 12-hr cycle)
    - Use increased peak charge voltage (i.e. 4.1 vs. 4.0 volts)
    - Age cells using charged stand prior to cycling (SOC and temperature are key)
    - Life test at different temperatures
      - *Higher temperatures may reduce degradation (how high)*
      - *Lower temperatures can increase degradation (how low)*
  - *Each method has advantages and disadvantages*
- **How can we be sure that failure modes are the same in real time test compared to accelerated test?**
- **Definition of the test acceleration factor A**

  A = real-time life/ accelerated life
  - *Requires completion of both a real time and an accelerated life test (not rapid)*

Degradation Trajectory Analysis (DETRAN)

- **Tracks the discharge voltage degradation trajectory of Li-ion cells during life testing**
- **Trajectory provides a measure of how cells degrade and fail**
  - *Basic DETRAN assumptions:*
    1. ***that both capacity loss and resistance increase contribute towards failure***
    2. ***that cell failure occurs when the increase in discharge voltage polarization reaches a threshold (influenced by capacity loss and resistance increase)***
    3. ***that a similar trajectory path over time reflects similar degradation processes***



Every cell has its own degradation trajectory.

Roles of DC resistance growth and capacity loss are both important.

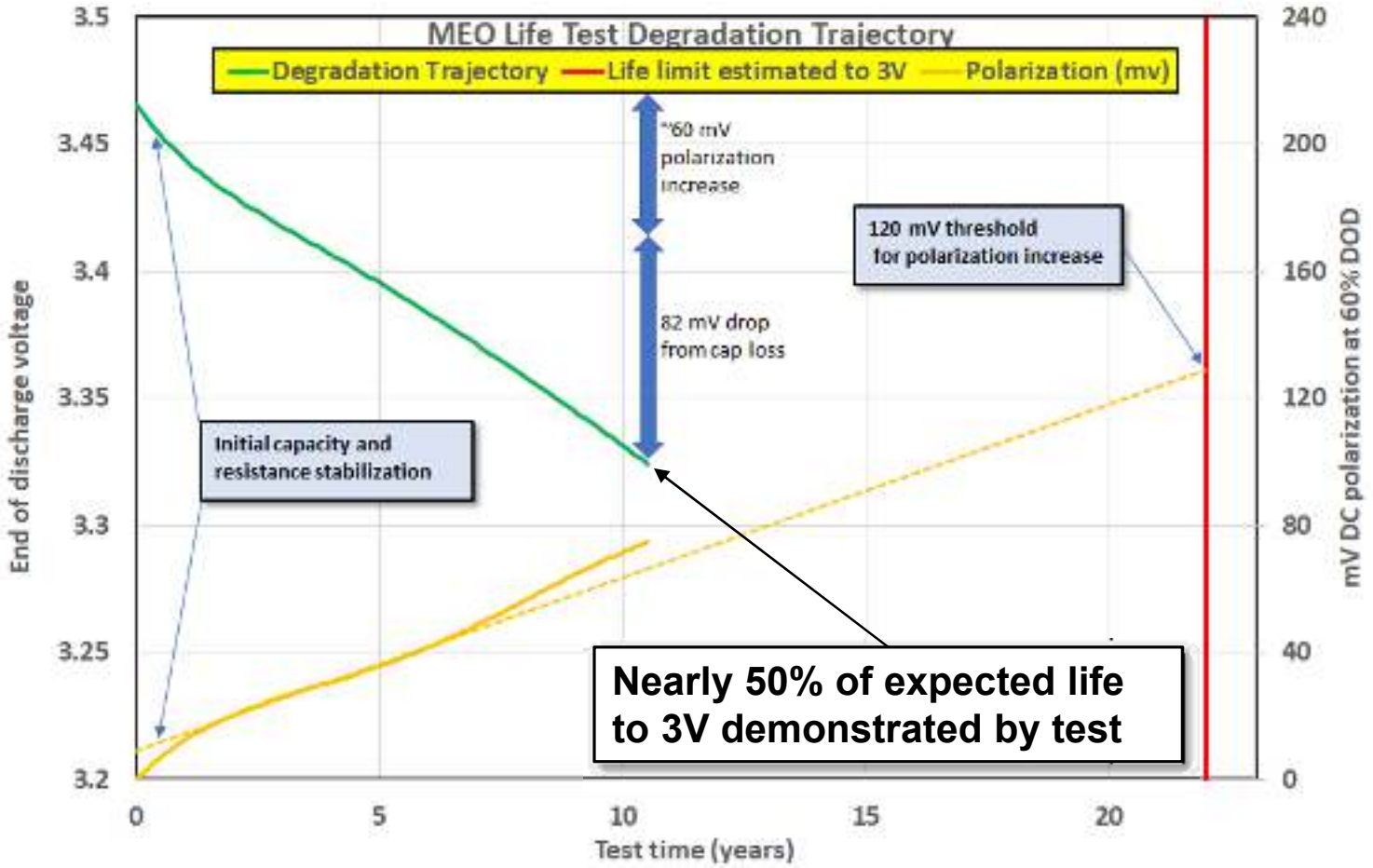
Threshold for increase in DC polarization

Uses for Degradation Trajectory Analysis

- **Provide alternate way to determine acceleration factor A**
  - *A = accelerated degradation rate/real-time degradation rate*
  - *Life tests only have to run long enough to stabilize degradation rates*
- **Predict life without running a life test all the way to failure**
- **Rapid evaluation of acceleration factors**
  - *From trajectory comparison for accelerated and real-time life tests*
- **Identification of degradation processes in life tests**
  - *Similar degradation processes tend to follow similar trajectories*
- **Identification of inappropriately accelerated life tests**
  - *If an anomalous trajectory path is seen in an accelerated life test*
- **Warning of potential hazards from Li-ion cells on life test**
  - *Li metal plating signatures can warn of danger from shorts or fire*

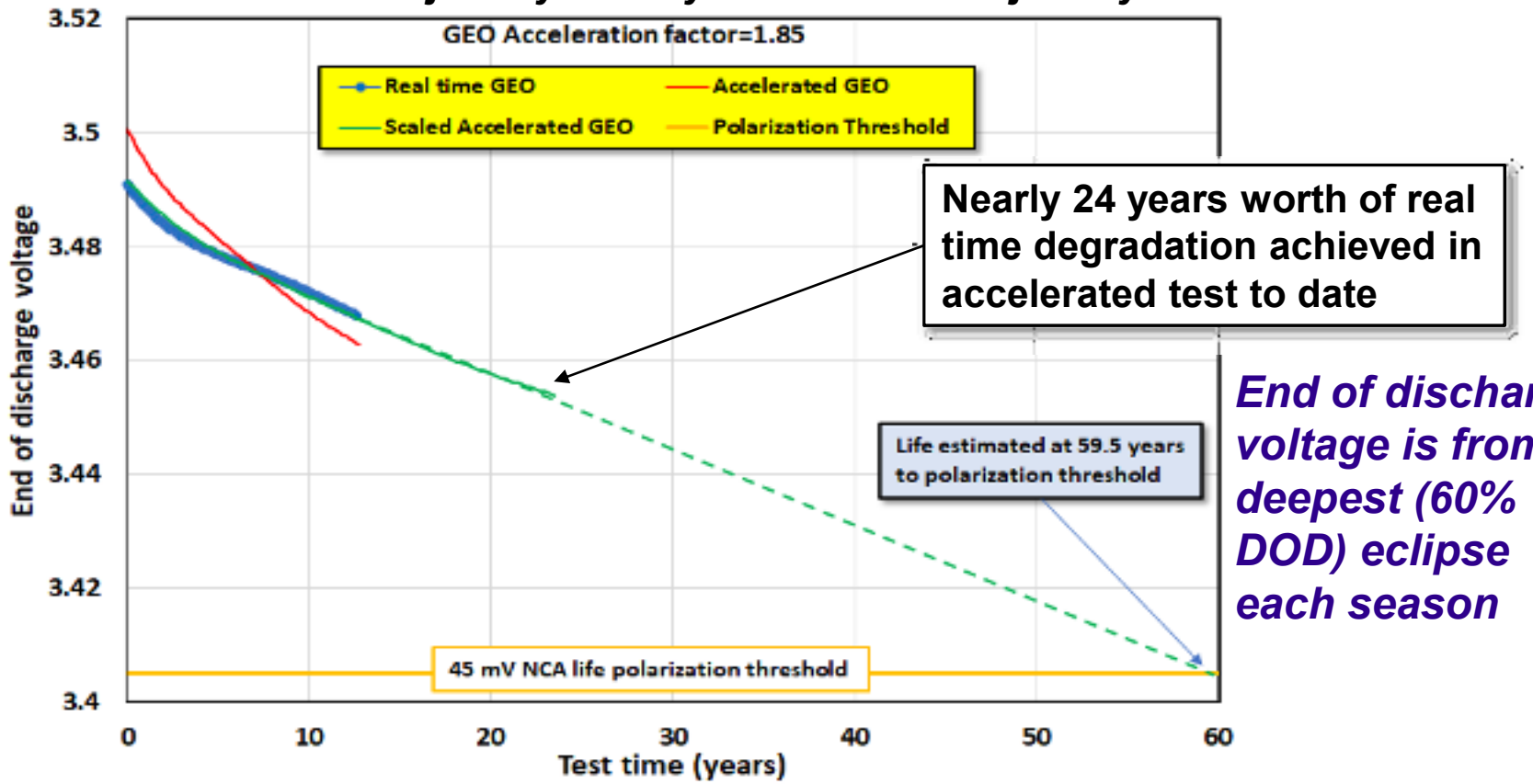
Life Prediction from Degradation Trajectory

- **Degradation trajectory can be used to predict end of life long before cell failure is observed**
  - ***Requires that trajectory shape or polarization threshold are known***



Acceleration Factors from Degradation Trajectory

- **Degradation trajectory can be used to determine acceleration factors**
  - ***Constant time-dilation by the correct acceleration factor should make the accelerated trajectory overlay the real-time trajectory***



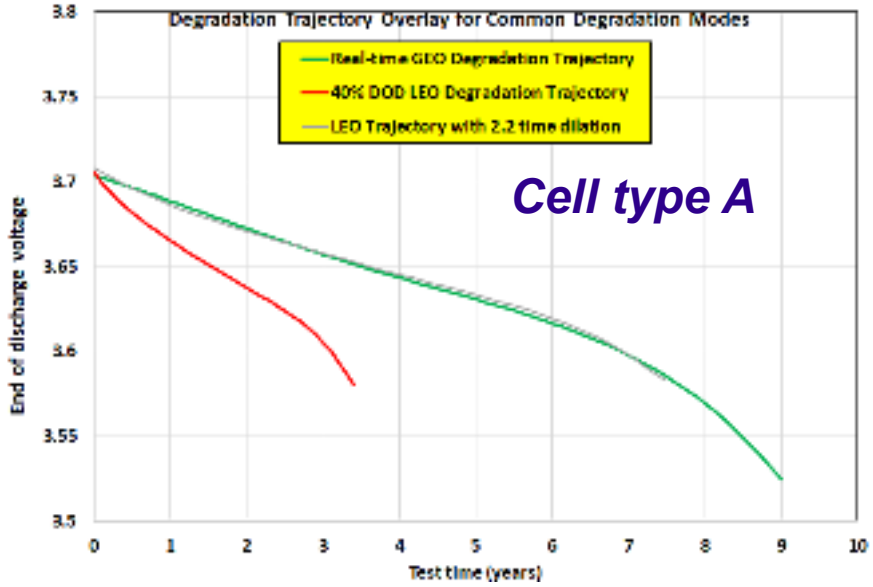
End of discharge voltage is from deepest (60% DOD) eclipse each season

- ***GEO test accelerated here by shortening solstice season to 2-days***
- ***All Li-ion cells tested have given 1.80 to 1.85 acceleration factor for this accelerated profile***

Trajectory Paths and Degradation Processes

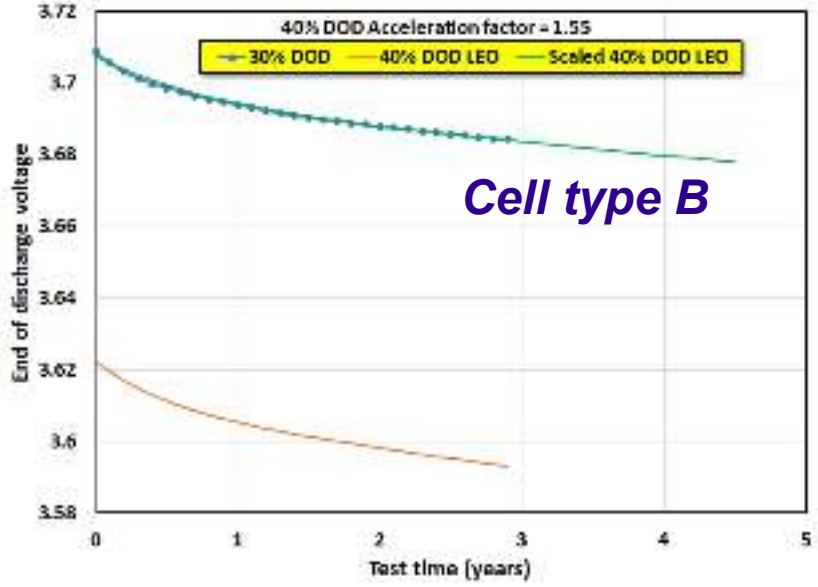
Similar degradation trajectories point to similar degradation processes

Scaled 40% DOD LEO degradation trajectory overlays real-time GEO trajectory all the way to failure



Failure verified by DPA to result from capacity loss due to SEI growth in both 40% DOD LEO and real-time GEO life tests

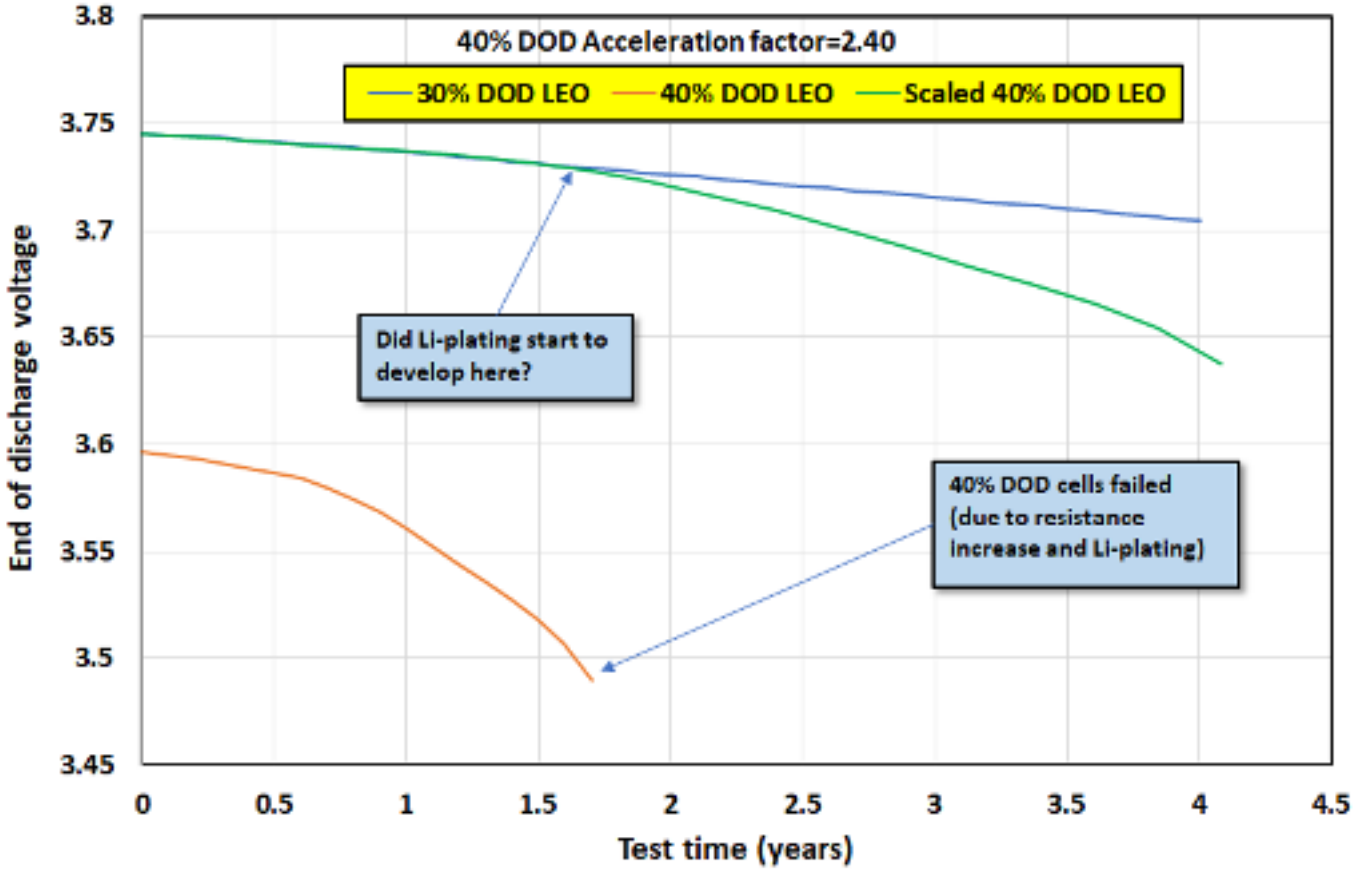
Scaled 40% DOD LEO degradation trajectory overlays 30% DOD LEO trajectory for 3-yr of data



Failure is expected to be caused by the same processes at both 30% and 40% DOD, because trajectories overlay each other

Anomalous Trajectory Paths

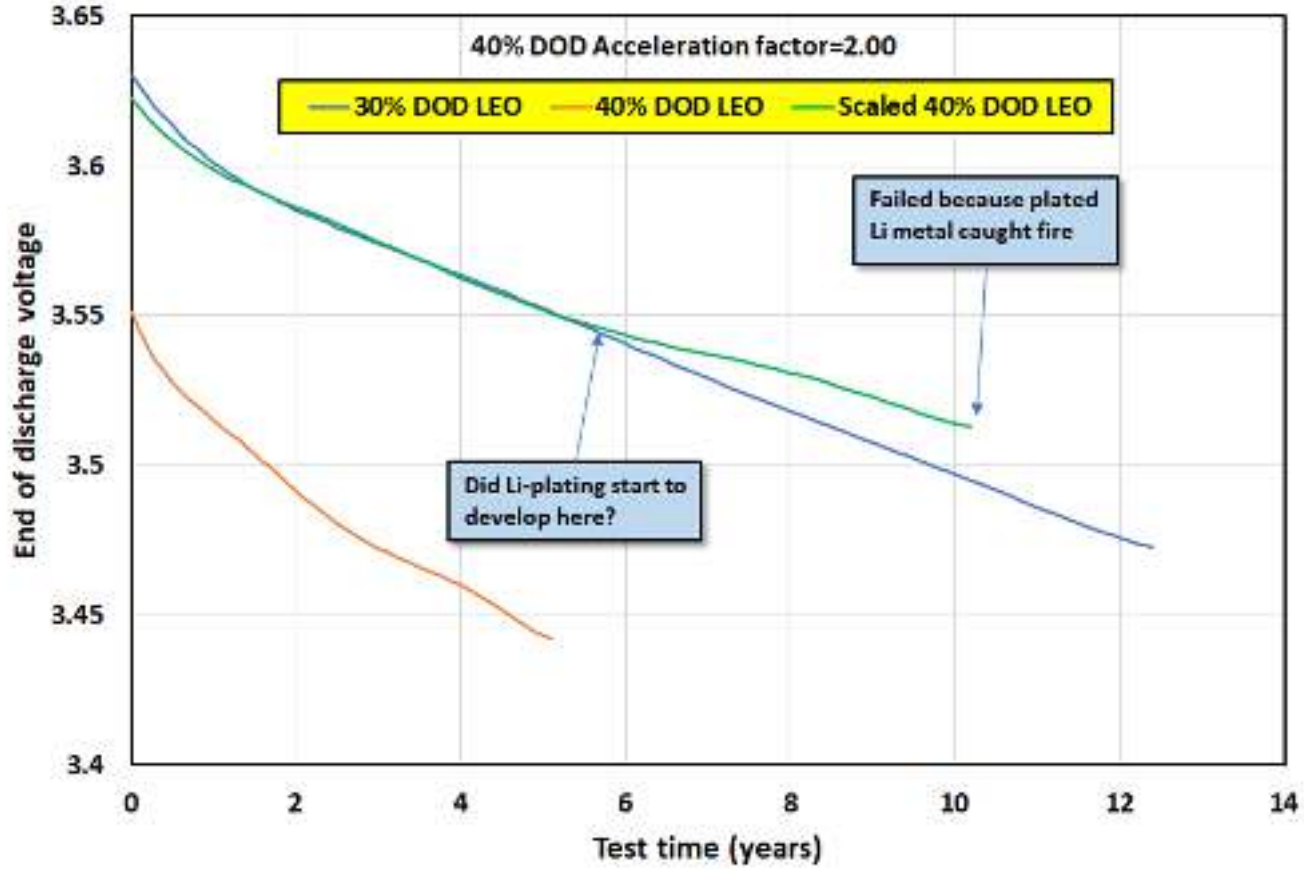
- **Degradation trajectories in stressful tests can have unexpected shapes, indicating that new failure modes can be developing**



Li-Ion cell shown here failed quickly in 40% DOD LEO profile due to resistance increase and Li-plating, but ran without failure at 30% DOD

Degradation Trajectory Paths for Early Warning

- **Degradation trajectories can warn of undesirable and potentially hazardous changes in cells during life testing**



Increase in discharge voltage trajectory for 40% DOD could have given ~2 year warning prior to cell failure, if compared to 30% DOD trajectory

Conclusions

- **Degradation Trajectory Analysis (DETRAN) can be used to better understand the degradation signatures provided by life tests**
- **Cell life estimates, particularly based on accelerated test data, can be performed using Degradation Trajectory Analysis**
- **Life test acceleration factors can be evaluated based on only a few years of life testing**
  - *Acceleration factors can be the same over many types of Li-ion cells for some test conditions*
- **Degradation Trajectory Analysis can indicate when accelerated test profiles are appropriate to real-time conditions, and when they are not**
- **Degradation Trajectory Analysis can provide significant advance warning of developing hazards, such as plated Li-metal accumulation**
- **Results can be used to detect undesirable degradation reactions before they cause cell failures**