

Life Performance of Li-Ion Cells in LEO, HEO/MEO, and GEO Orbital Profiles

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Topics to be Discussed

- **Purpose of test program**
- **Cell types being tested**
- **Orbital profiles**
- **Cell test procedures**
 - *Charge/discharge profiles*
 - *Operational capacity measurements*
 - *Thermal control*
- **Test results to date**
- **Conclusions**



Purposes of Test Effort

- **Obtain generic life performance data to aid in transitioning Li-Ion batteries into satellites**
- **Evaluate types of domestic cells available for long term satellite performance capability**
 - *Cells must show good performance in long-term feasibility tests to be included in this test program*
- **Identify multiple cell designs capable of providing needed performance**
- **10-year minimum planned test duration**
 - *Test is planned to run to cell failure*
 - *Failure criterion: Cell fails to stay above 3.0 volts during discharge after being charged to 4.1 volts*



Cells On Test (166 total cells)

Test Description	Quallion 12.00 Ah	Lithion 49.15 Ah	SAFT 40.65 Ah GEO/HEO 35.83 Ah LEO	MSA 56.66 Ah
<ul style="list-style-type: none"> • GEO real-time, 60% DOD • GEO accelerated, 60% DOD 	5 cells 6 cells	5 cells 6 cells	5 cells 6 cells	5 cells 6 cells
<ul style="list-style-type: none"> • HEO/MEO real-time, 60% DOD • HEO/MEO accelerated, 60% DOD 	5 cells 6 cells	5 cells 6 cells	5 cells 6 cells	5 cells 6 cells
<ul style="list-style-type: none"> • LEO 30% DOD • LEO 40% DOD 	5 cells 6 cells	5 cells 6 cells	5 cells 6 cells	5 cells 6 cells
<ul style="list-style-type: none"> • Ground storage test packs (3.5 V) • Orbital storage (3.8 V) 	5 cells ---	--- ---	19 cells ---	5 cells 5 cells

MSA cells are MSA50-1

SAFT cells are from Cockeysville facility: VL48E and VL48E(L)

Lithion cells are NCP55-2

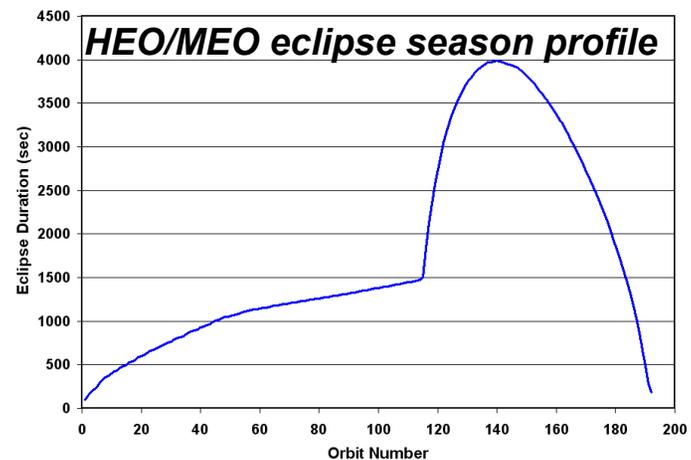
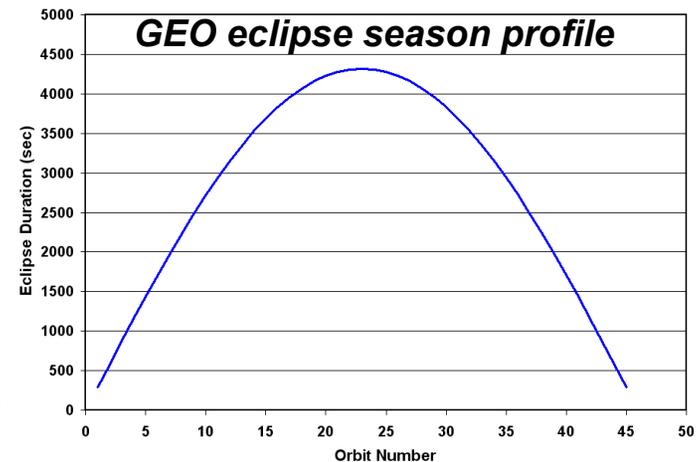
Quallion cells are QL015-KA

Nameplate capacity ratings are 5/6 of average actual capacity



Summary of Orbital Profiles

- **GEO tests – 60% DOD**
 - *Real time:* Two 45-day eclipse seasons per yr, with 138-day solstice season
 - *Accelerated:* Solstice season reduced to 2 days
- **HEO/MEO tests – 60% DOD**
 - *Real time:* 192-cycle eclipse season, 39-day solstice season (12 hr cycles)
 - *Accelerated:* 192-cycle eclipse season, 19.5-day solstice season (6 hr cycles)
- **LEO tests: 96-min. cycle (35 min. disch.)**
 - **30% DOD:** 51.4% C discharge
 - **40% DOD:** 68.6% C discharge
- **Orbital Storage**
 - *Continuous storage at 3.8 volts*



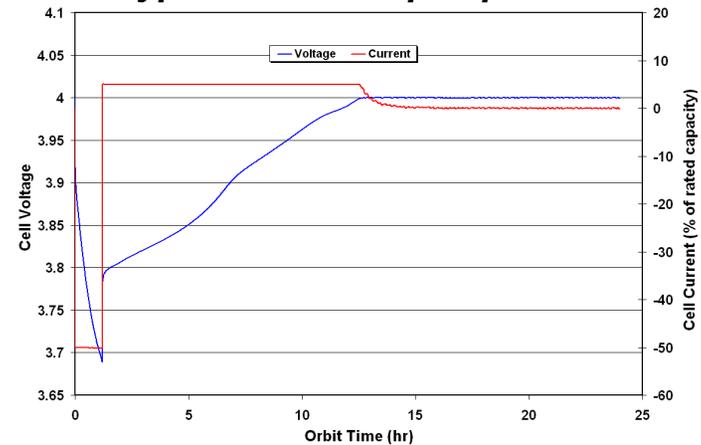
Operational capacity measured roughly twice per yr in each test



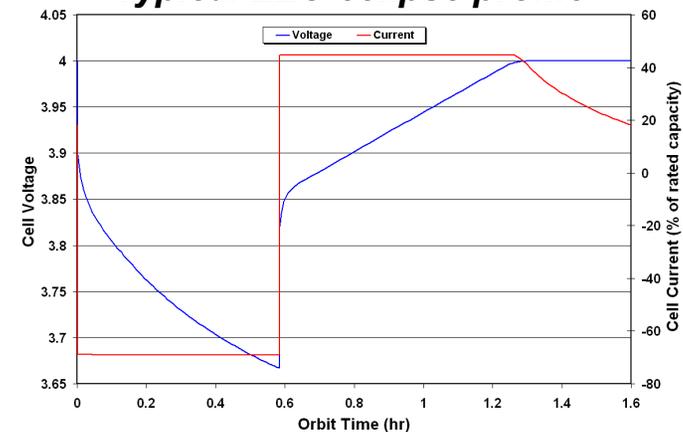
Charge Control

- **Constant current to peak voltage, followed by taper at constant voltage**
- **Peak voltage increased as needed to maintain 20% reserve capacity**
- **GEO tests**
 - *C/20 constant current*
 - *4.0 peak charge voltage to date*
- **HEO/MEO tests**
 - *Real time: C/15 constant current*
 - *Accelerated: C/7.5 constant current*
 - *4.0 peak charge voltage to date*
- **LEO tests**
 - *30% DOD: 33.2% C constant current*
 - *40% DOD: 44.2% C constant current*

Typical GEO eclipse profile



Typical LEO eclipse profile

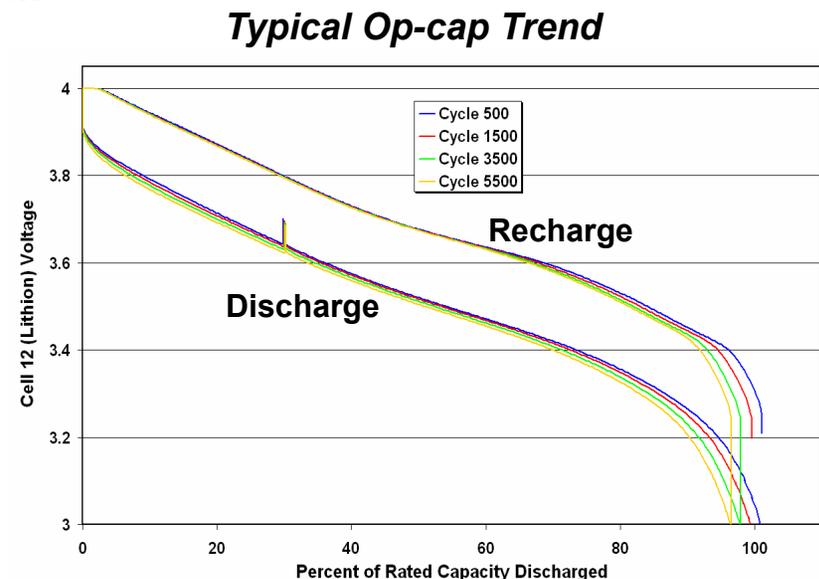


4.0 peak charge voltage used to date (3.9 for SAFT LEO cells)



Operational Capacity Measurements

- Discharge at normal rate to 3.0 volts
- Recharge at normal charge rate until current has tapered
- Pulse impedance measurement 30 minutes into discharge
- **GEO tests**
 - *Real-time: After each eclipse season*
 - *Accelerated: after every 4th eclipse season*
- **HEO/MEO tests**
 - *Real time: After every eclipse season*
 - *Accelerated: after every 3rd eclipse season*
- **LEO tests:** After 500, 1000, then every 2000 cycles



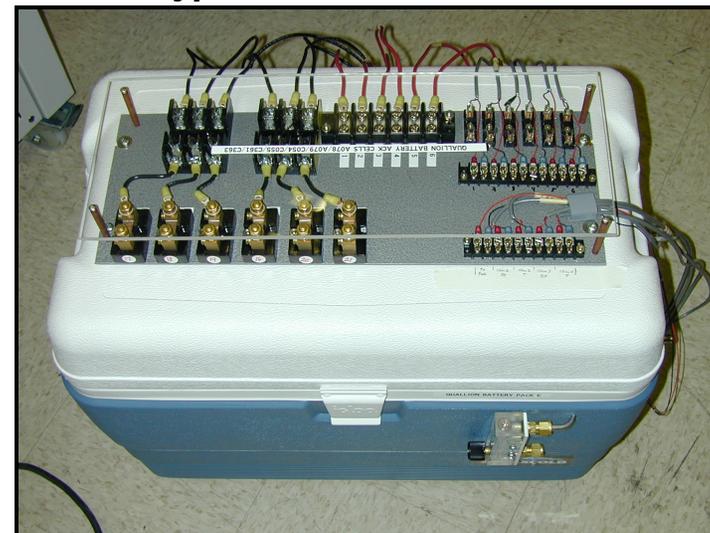
Test Pack Thermal Control

- Cell pack mounted on aluminum-clad copper base plate
- Base plate controlled at 20°C
 - Cells typically warm-up ~5°C during discharge to 60% DOD
- All heat is dissipated by conduction to base plate
 - Cell pack insulated to prevent convective dissipation
 - Insulated pack in aluminum enclosure
 - Enclosure in thermally insulated box
- Test box contains N₂ atmosphere
- All wires from cell pack are fused

Typical Cell Pack

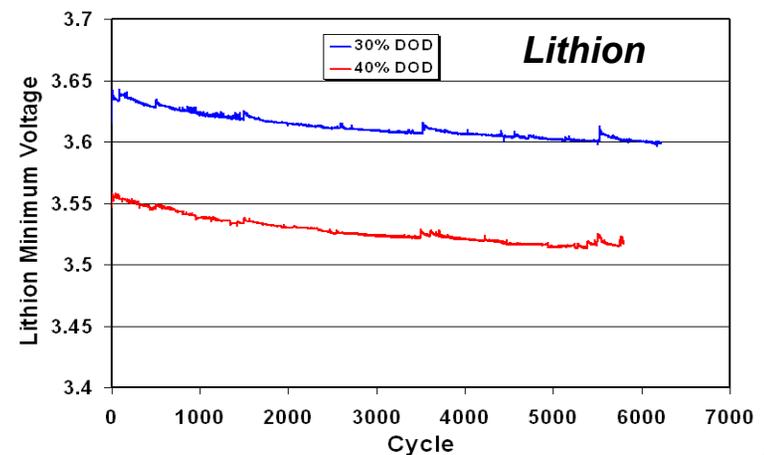
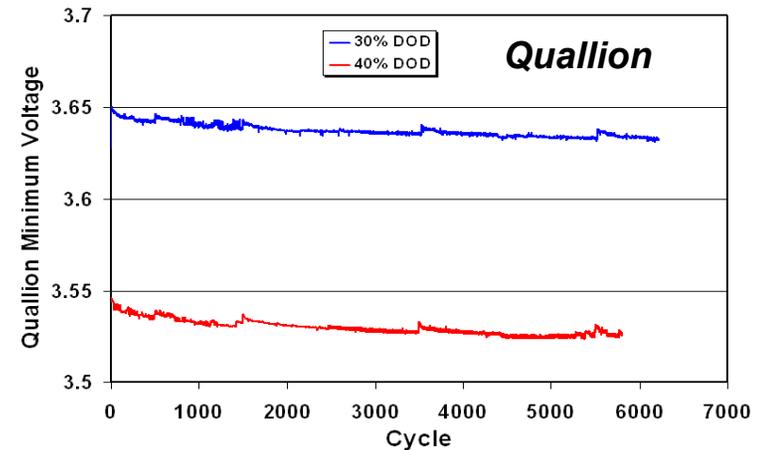


Typical Finished Test Box



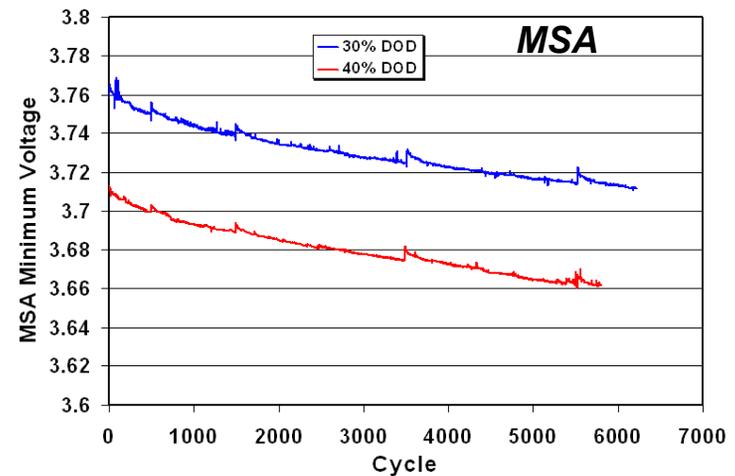
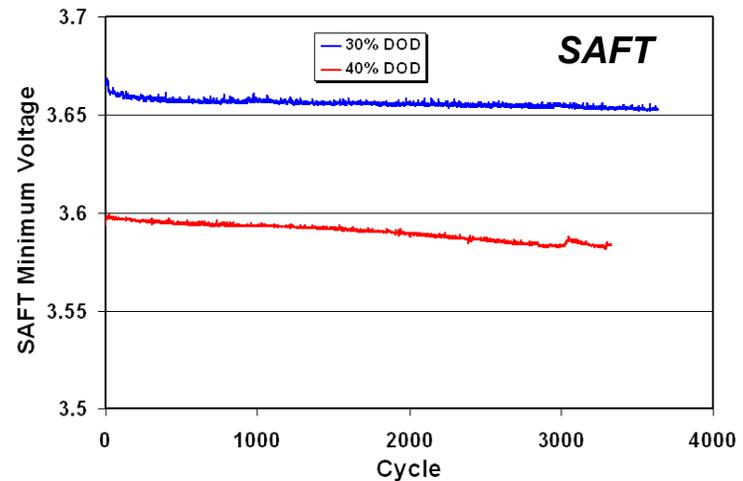
Test Results – LEO Tests

- Average cell voltages are shown for each test pack
- All cells are performing well to date
- Operational capacity measurements often cause a small temporary increase in minimum discharge voltage
- Performance at 40% DOD is not degrading much faster than at 30% DOD



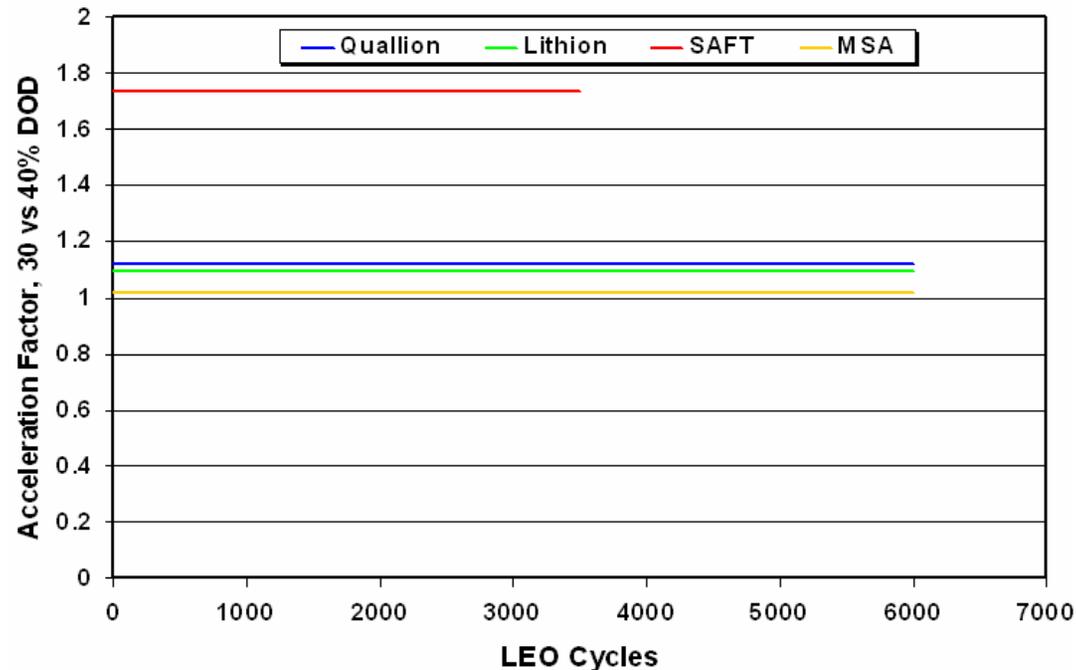
Test Results – LEO Tests (cont.)

- Average cell voltages are shown for each test pack
- All cells are performing well to date
- Operational capacity measurements often cause a small temporary increase in minimum discharge voltage
- Performance for SAFT cells at 40% DOD appears to be degrading faster than at 30% DOD
 - Voltage decay rate is low at either DOD



LEO Acceleration Factors

Degradation rate at 40% DOD relative to that at 30% DOD

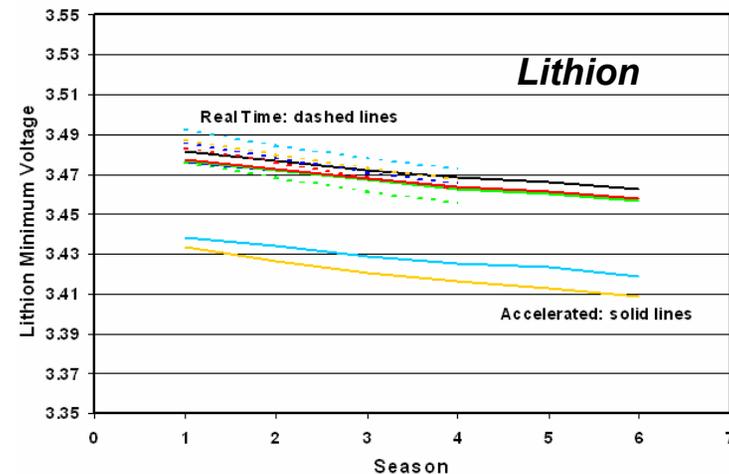
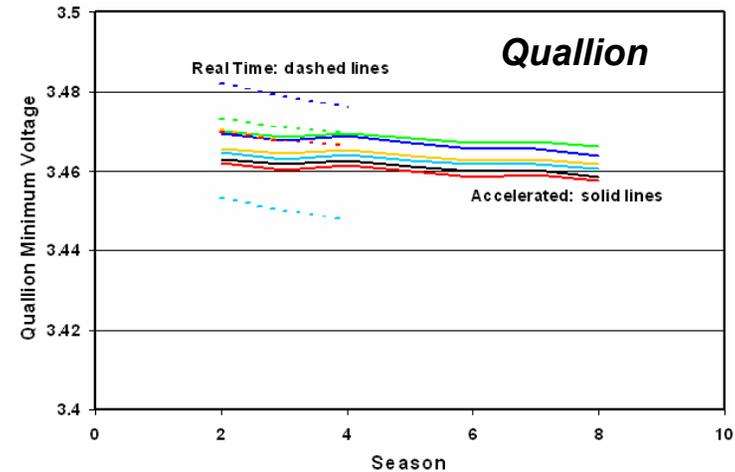


- All the prismatic cells appear to have LEO acceleration factors between 1.0 and 1.1 after 6000 cycles
- The cylindrical SAFT cells appear to have a LEO acceleration factor between 1.7 and 2.0 after 3500 cycles



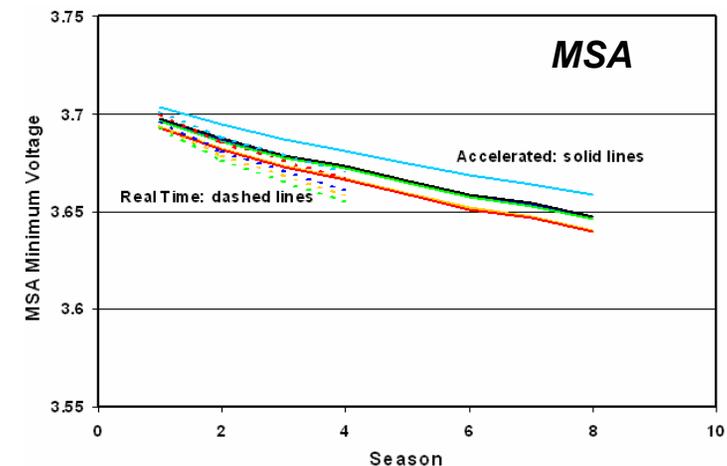
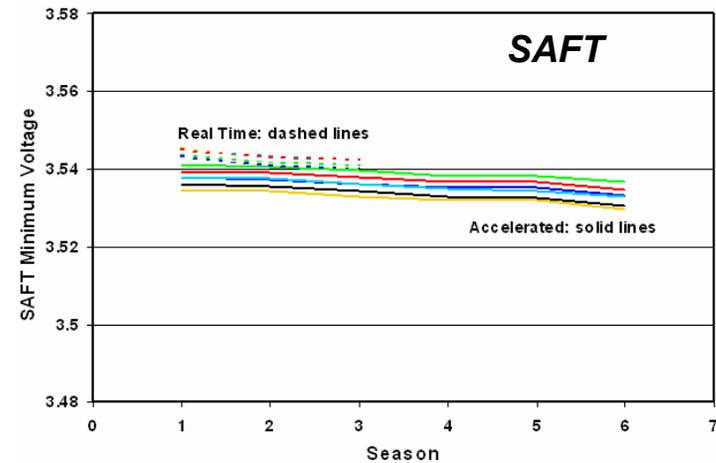
Test Results – HEO/MEO Tests

- All cells are performing well to date
- Operational capacity measurements do not appear to affect the minimum discharge voltage
- Performance in accelerated test is not degrading much faster than in real time test



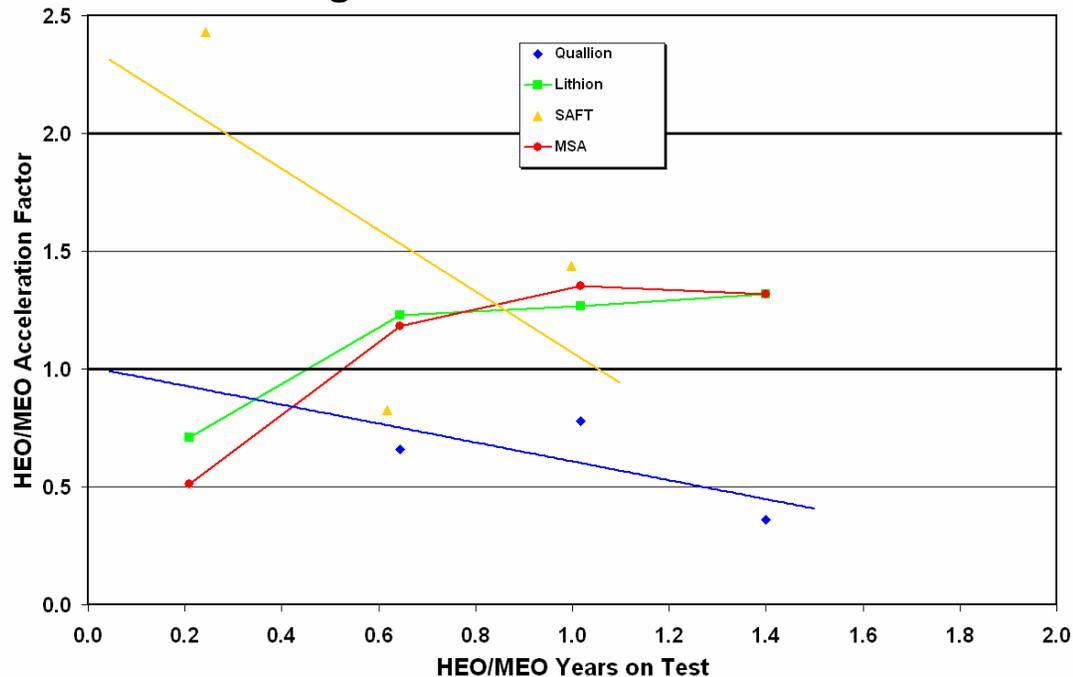
Test Results – HEO/MEO Tests (cont.)

- All cells are performing well to date
- Operational capacity measurements do not appear to affect the minimum discharge voltage
- MSA cells may be degrading slightly faster in real-time test



HEO/MEO Acceleration Factors

Defined as additional degradation in accelerated test over real-time test



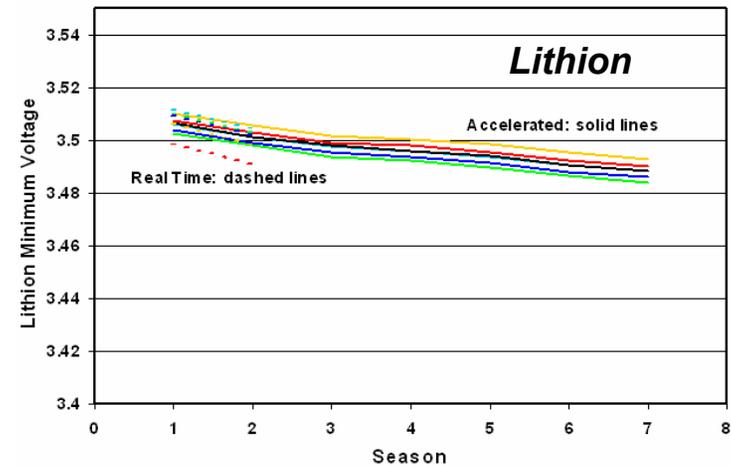
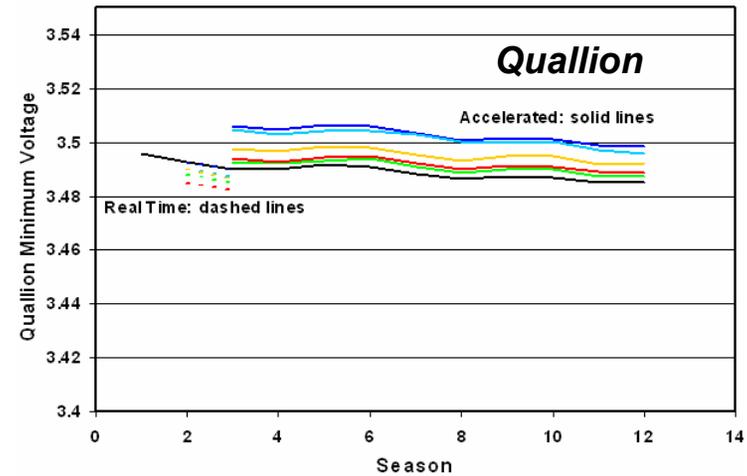
- The Lithion, SAFT, and MSA cells seem to have a 1.0 to 1.5 acceleration factor after 1.4 years on test
- The Quallion cells show improved performance so far with the additional cycles in the accelerated test (<1.0 acceleration factor)

*Acceleration factor of 2.0 expected if degradation is controlled by cycles,
1.0 if purely controlled by calendar life*



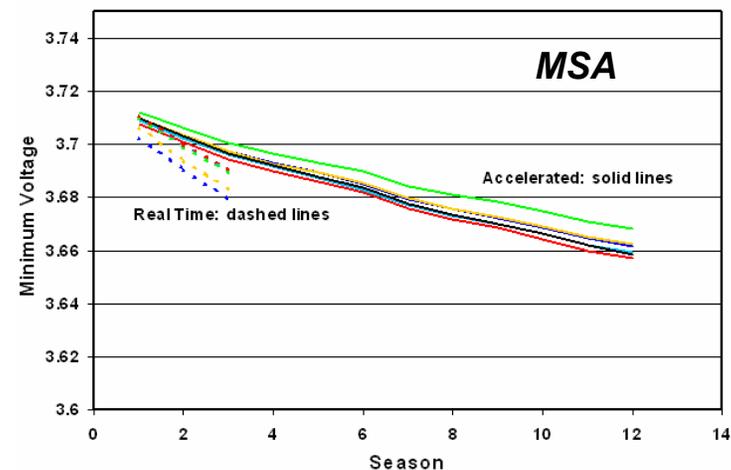
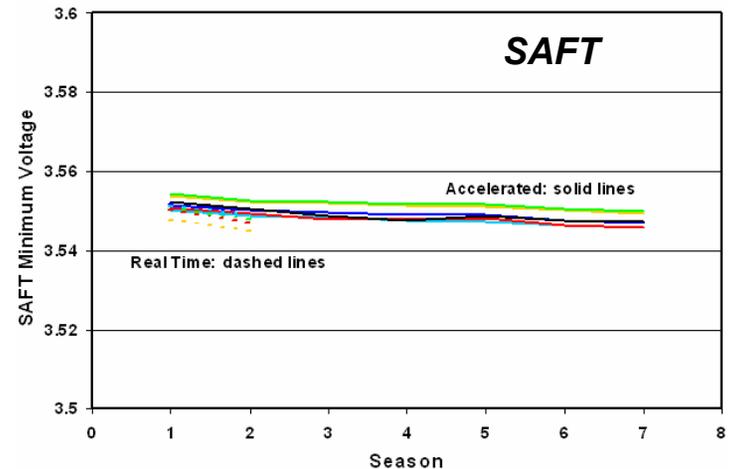
Test Results – GEO Tests

- All cells are performing well to date
- Operational capacity measurements do not appear to affect the minimum discharge voltage
- Need more data to compare the accelerated test to the real time test



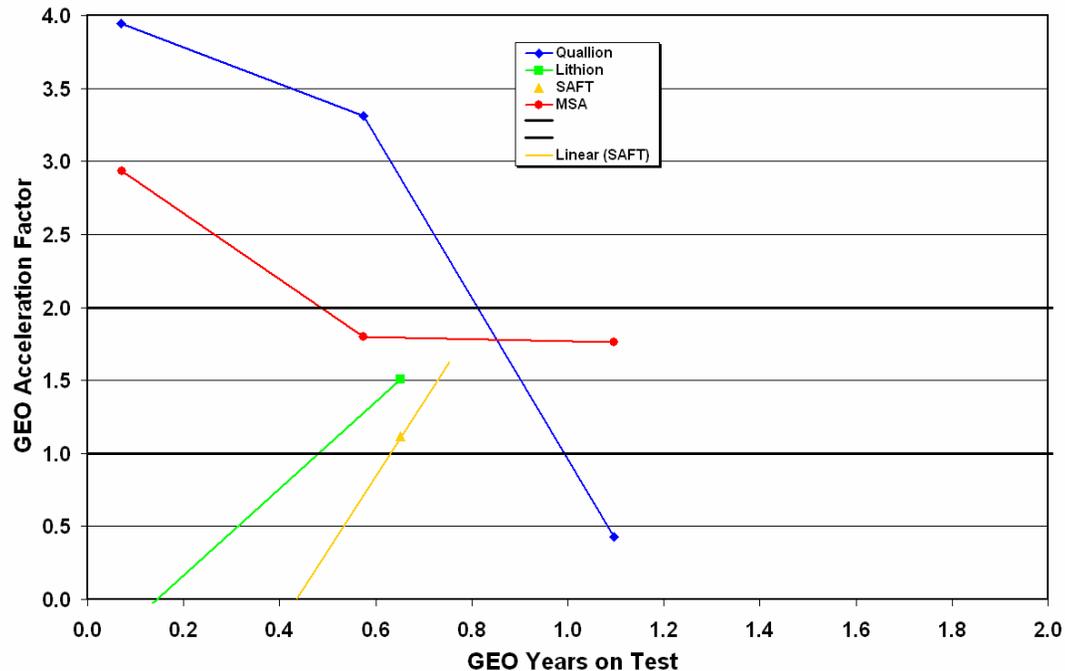
Test Results – GEO Tests (cont.)

- All cells are performing well to date
- Operational capacity measurements do not appear to affect the minimum discharge voltage
- MSA cells may be degrading slightly faster in real-time test
- Need more data to compare the accelerated test to the real time test



GEO Acceleration Factors

Defined as additional degradation in accelerated test over real-time test



- The Lithion, SAFT, and MSA cells seem to have a 1.0 to 2.0 acceleration factor after 0.6 to 1.1 years on test
- The Quallion cells may show improved performance so far with the added cycles in the accelerated test (<1.0 acceleration factor)

*Acceleration factor of 3.88 expected if degradation is controlled by cycles,
1.0 if purely controlled by calendar life*



Conclusions and Further Analysis

- **After 1.5 yrs of life testing – all cells are performing well**
- **Acceleration factors based on early life data**
 - *Low values suggest calendar life effects are greater than cycle life effects*
- **Further data are needed for life projections**
- **Ongoing modeling efforts will examine degradation mechanisms**
 - *Space Power Workshop, April 2009*

