

An Update on the Lithium-Ion Cell Low-Earth-Orbit Verification Test Program

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An Update on the Lithium-Ion Cell Low-Earth-Orbit Verification Test Program

A Lithium-Ion Cell Low-Earth-Orbit Verification Test Program is being conducted by NASA Glenn Research Center to assess the performance of lithium-ion (Li-ion) cells over a wide range of low-Earth-orbit (LEO) conditions. The data generated will be used to build an empirical model for Li-ion batteries. The goal of the modeling will be to develop a tool to predict the performance and cycle life of Li-ion batteries operating at a specified set of mission conditions. Using this tool, mission planners will be able to design operation points of the battery system while factoring in mission requirements and the expected life and performance of the batteries.

Test conditions for the program were selected via a statistical design of experiments to span a range of feasible operational conditions for LEO aerospace applications. The variables under evaluation are temperature, depth-of-discharge (DOD), and end-of-charge voltage (EOCV). The baseline matrix was formed by generating combinations from a set of three values for each variable. Temperature values are 10 °C, 20 °C and 30 °C. Depth-of-discharge values are 20%, 30% and 40%. EOCV values are 3.85 V, 3.95 V, and 4.05 V. Test conditions for individual cells may vary slightly from the baseline test matrix depending upon the cell manufacturer's recommended operating conditions. Cells from each vendor are being evaluated at each of ten sets of test conditions.

Cells from four cell manufacturers are undergoing life cycle tests. Life cycling on the first sets of cells began in September 2004. These cells consist of Saft 40 ampere-hour (Ah) cells and Lithion 30 Ah cells. These cells have achieved over 10,000 cycles each, equivalent to about 20 months in LEO. In the past year, the test program has expanded to include the evaluation of Mine Safety Appliances (MSA) 50 Ah cells and ABSL battery modules. The MSA cells will begin life cycling in October 2006. The ABSL battery modules consist of commercial Sony hard carbon 18650 lithium-ion cells configured in series and parallel combinations to create nominal 14.4 volt, 3 Ah packs (4s-2p). These modules have accumulated approximately 3000 cycles.

Results on the performance of the cells and modules will be presented in this paper. The life prediction and performance model for Li-ion cells in LEO will be built by analyzing the data statistically and performing regression analysis. Cells are being cycled to failure so that differences in performance trends that occur at different stages in the life of the cell can be observed and accurately modeled. Cell testing is being performed at the Naval Surface Warfare Center in Crane, IN.



Lithium-Ion LEO Verification Test Program

- Initiated in 2002
- Flexible program for the assessment of Li-Ion technology capabilities for Low Earth Orbit
 - Provide information about multiple vendors
 - Provide for assessment of technology developments
- Statistical Design of Experiments approach addresses program test goals and resource limitations
- Data will be used to develop an empirical model to predict life of cells as a function of DOD, temperature, and EOCV
- Testing is conducted at the NSWC in Crane, IN

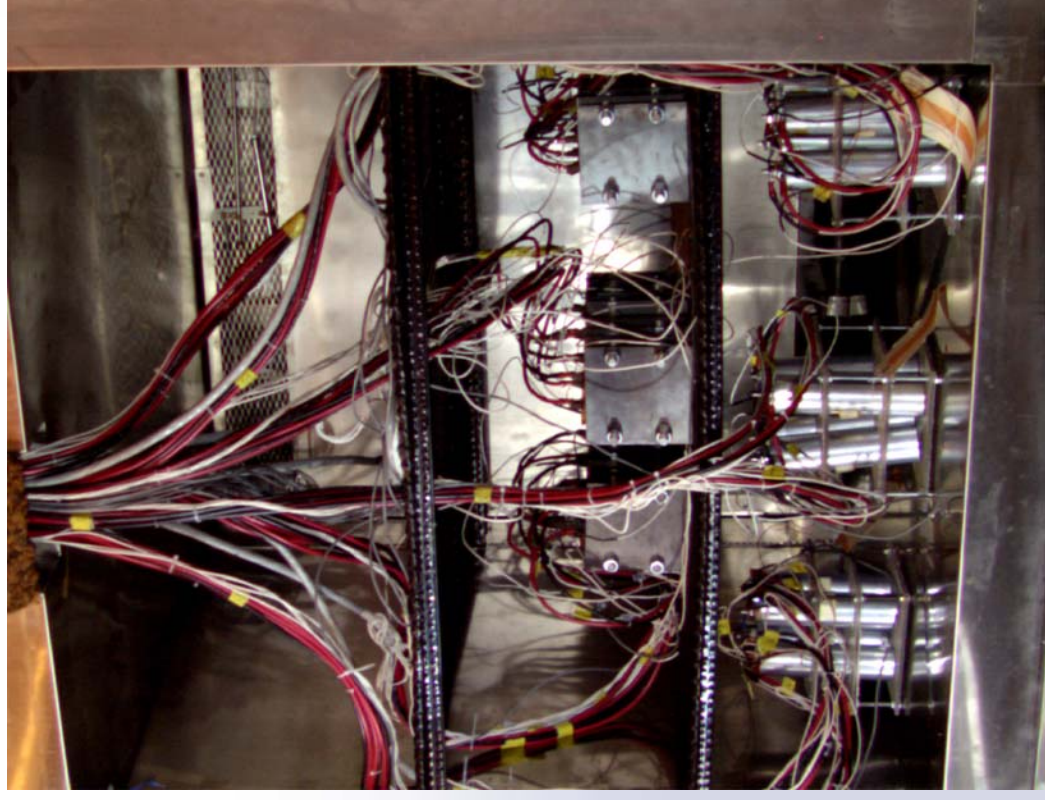


Representative products from each vendor. Left to Right: ABSL modules, Saft cell, Lithion cell, MSA cells



Test Articles

- 40 Lithion (30 Ah) cells
 - INCP 95/28/154
 - Delivered 4/02
- 40 Saft (40 Ah) cells
 - G4 chemistry space cells (HE54245)
 - Delivered 4/02
- 40 MSA (50 Ah) cells
 - 50G01
 - Delivered 10/05
- 20 4s-2p modules with 1.5 Ah Sony hard carbon 18650 cells from ABSL
 - 4S-2P-SSTB
 - Delivered 7/05



Test Set-up

Saft, Lithion and MSA cells

- Four cells are tested at each set of conditions
- Cells are connected in series, however the charging of each cell is controlled individually with the use of charge control electronics
- Cells at each test condition are individually packaged and housed in the same chamber
- Temperature is monitored on each cell

ABSL modules

- 2 ABSL modules connected in parallel are tested at each condition
- Individual cell voltages are monitored
- Charging and discharging is controlled at the module combination level
- Temperature is monitored on each module





Characterization and Testing

LEO Test Matrix

- Acceptance Testing
- Characterization Testing
- Actual Capacity Determination
- Self-Discharge Rate
- Capacity at LEO test conditions
- LEO Life Cycling
 - Charge and discharge rates are calculated using the average actual discharge capacity of the cells at 20 °C
- Operational capacity checks

Temp(°C)	End-of-Charge Voltage/cell (V)	DoD (%)
30	4.05 ³ /4.0 ⁴	20
30	3.85	20
10	3.85	20
30	3.95	30
20	3.95	20
10	3.85	40 ¹ /35 ²
20	3.85	30
30	3.85	40 ¹ /35 ²
20	4.05 ³ /4.0 ⁴	40 ¹ /35 ²
10	4.05 ³ /4.0 ⁴	30

1 – All vendors except Saft 3 – All vendors except MSA
 2 - Saft 4 - MSA



Actual Capacity Determination Procedure

Test Temperature (°C)	20
Charge Cutoff Voltage (V)	Manufacturer's Recommended Voltage Saft, Lithion - 4.1, MSA - 4.0, ABSL - 4.2 (used 4.1)
Discharge Cutoff Voltage (V)	3.0
Sequence	<p>Stabilize to 20°C</p> <p>Start with C = nameplate</p> <p>C/2 discharge to 3V</p> <p>C/5 charge to recommended cut-off voltage</p> <p>Clamp, taper to C/50</p> <p>Open Circuit for 60 minutes</p> <p>C/2 discharge to 3V-capacity from this step becomes C value</p> <p>Repeat cycling until change in capacity from C/2 discharge steps $\leq 1\%$</p>



Testing Status as of October 2006

Saft and Lithion Cells

- LEO testing started in September 2004
- Cells have accumulated approximately 11000 cycles

MSA Cells

- Characterization testing complete
- LEO cycling will begin in November 2006

ABSL Modules

- LEO cycling began in April 2006
- Modules have completed approximately 2800 cycles





Results of Capacity Characterization

- Capacity results for each vendor at temperatures of -30 °C, -10 °C, 0 °C, 10 °C, 20 °C, 30 °C, 40 °C, 50 °C (Saft and MSA cells would not cycle at -30 °C)
- Capacity is measured at C/2 and 20 °C from 4.1 V to 3.0 V (from 4.0 V to 3.0 V for MSA cells). Cells are charged at C/5 for capacity characterization.
- ABSL capacity results are for two parallel modules (four parallel strings)

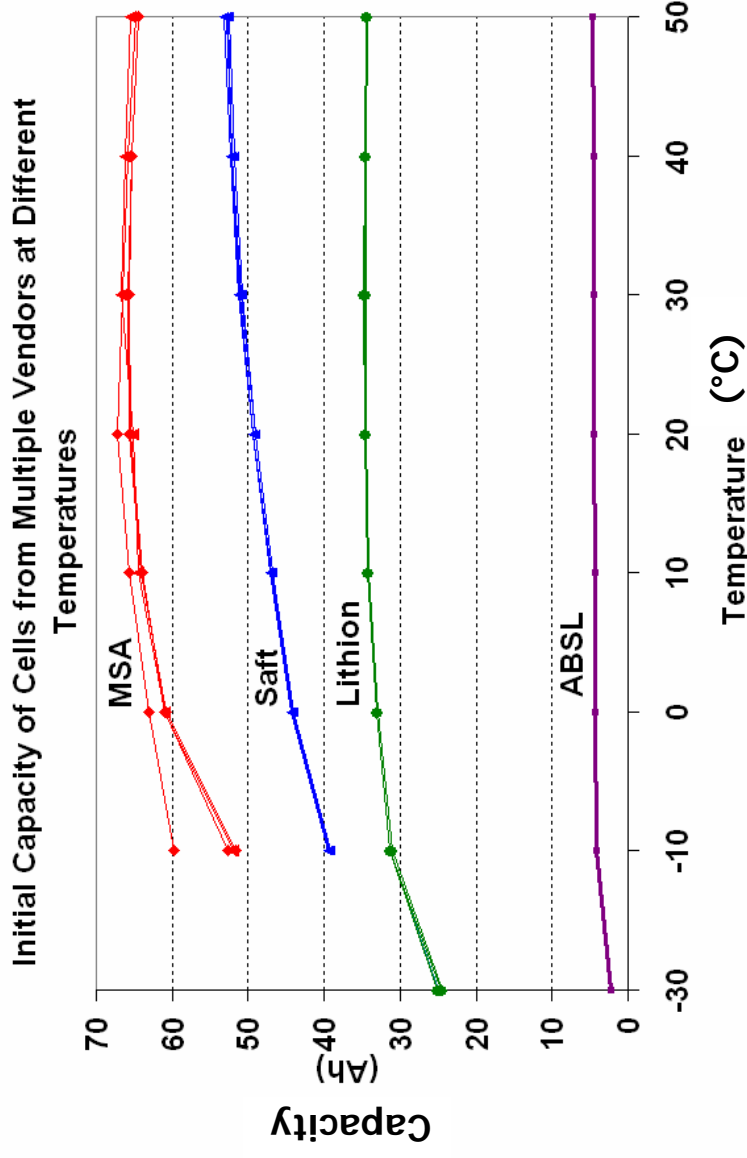
Average Capacity at 20 °C

Saft: 45.9 Ah

Lithion: 32.7 Ah

MSA: 66.4 Ah

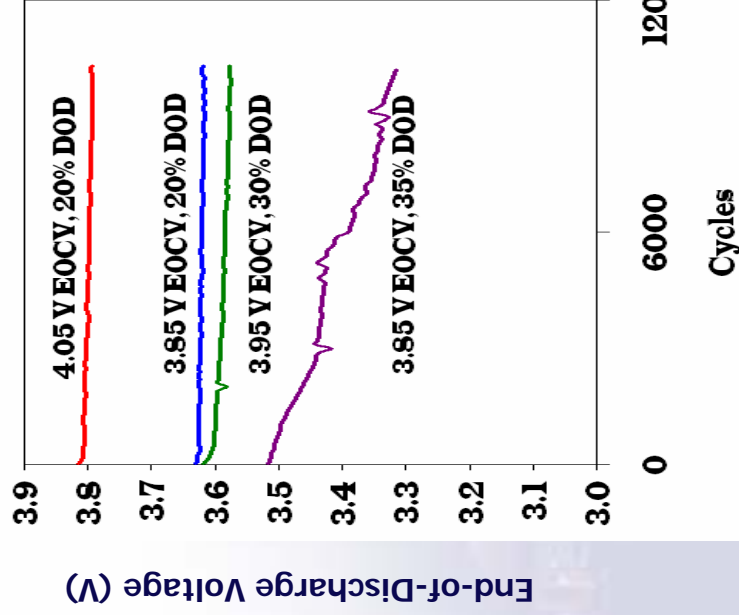
ABSL: 4.31 Ah



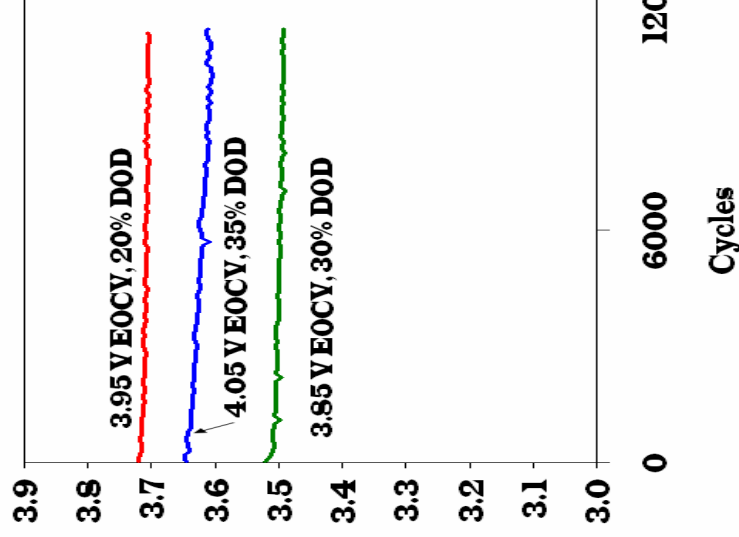


Soft End-of-Discharge Voltages versus Cycles as a Function of Temperature

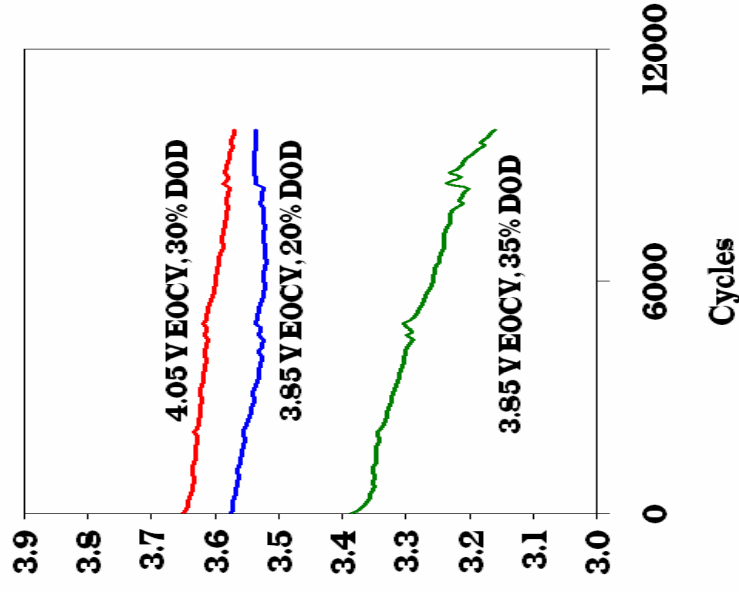
Soft End-of-Discharge Voltage at
30 Degrees C



Soft End-of-Discharge Voltage at
20 Degrees C



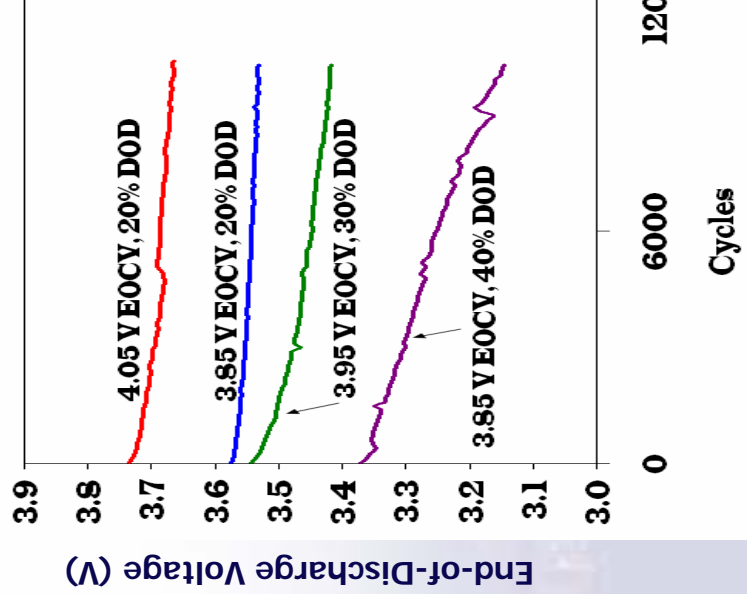
Soft End-of-Discharge Voltage at
10 Degrees C



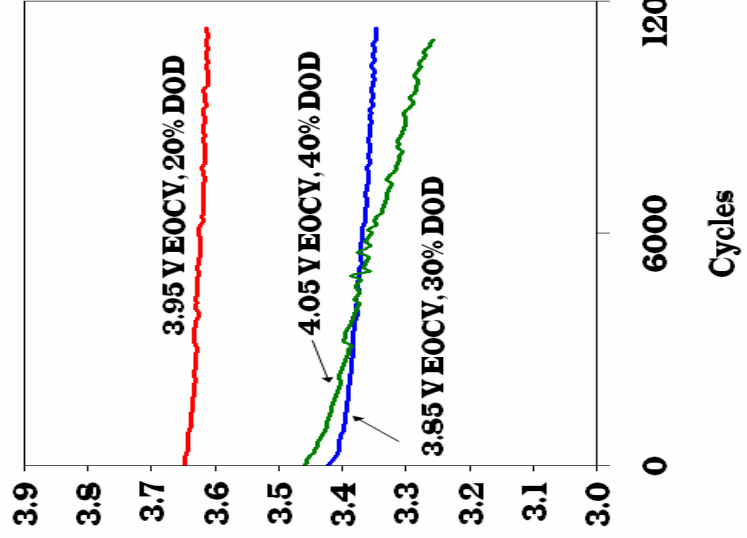


Lithion End-of-Discharge Voltages versus Cycles as a Function of Temperature

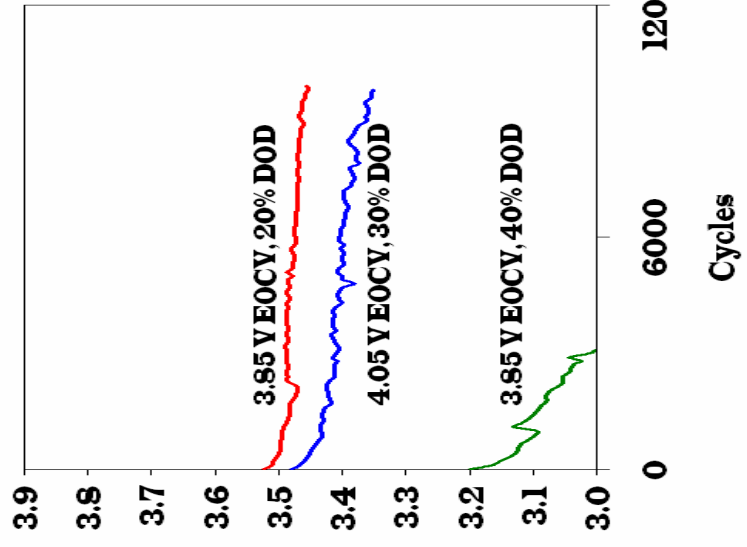
Lithion End-of-Discharge Voltage at 30 Degrees C



Lithion End-of-Discharge Voltage at 20 Degrees C

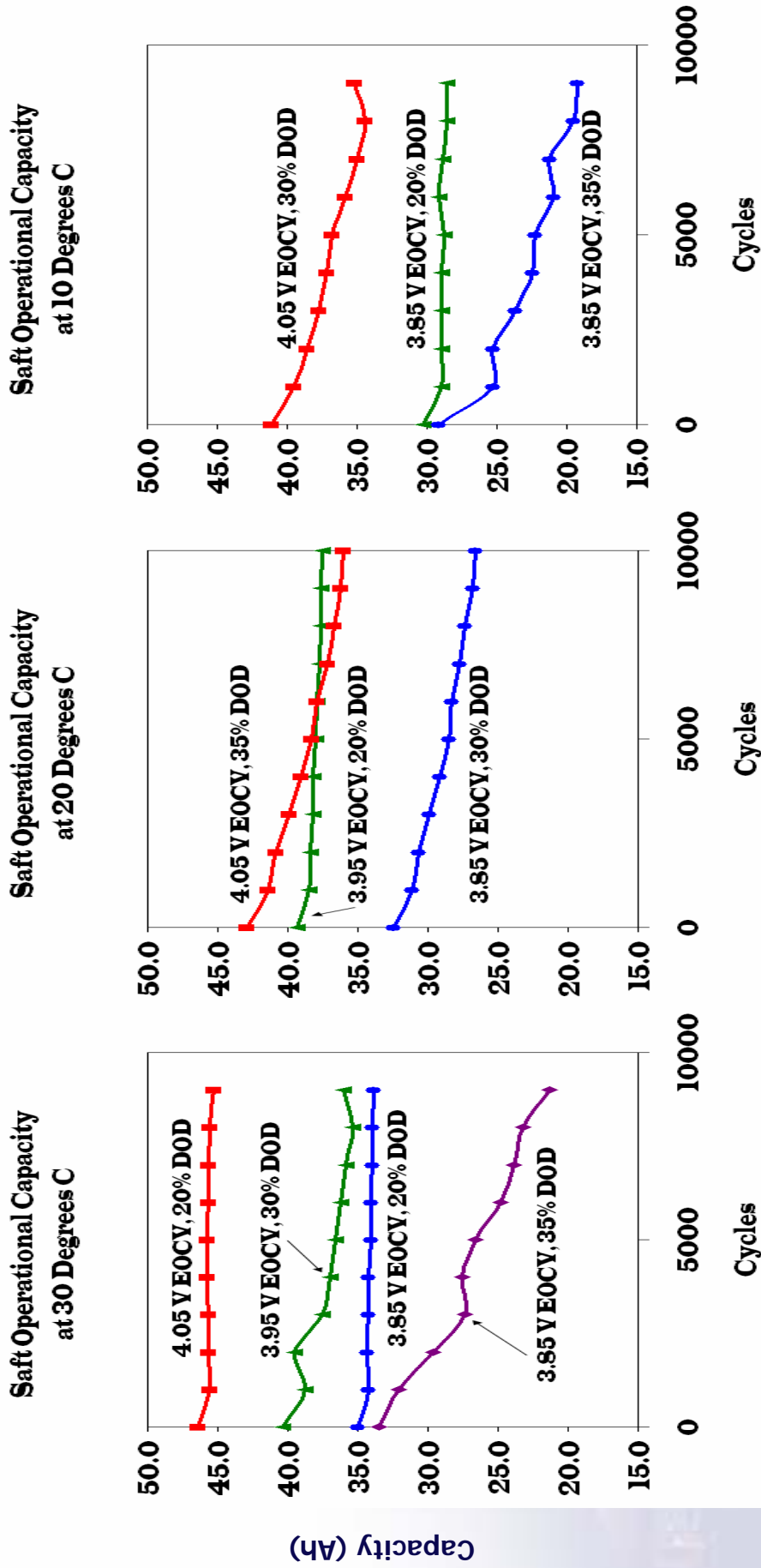


Lithion End-of-Discharge Voltage at 10 Degrees C



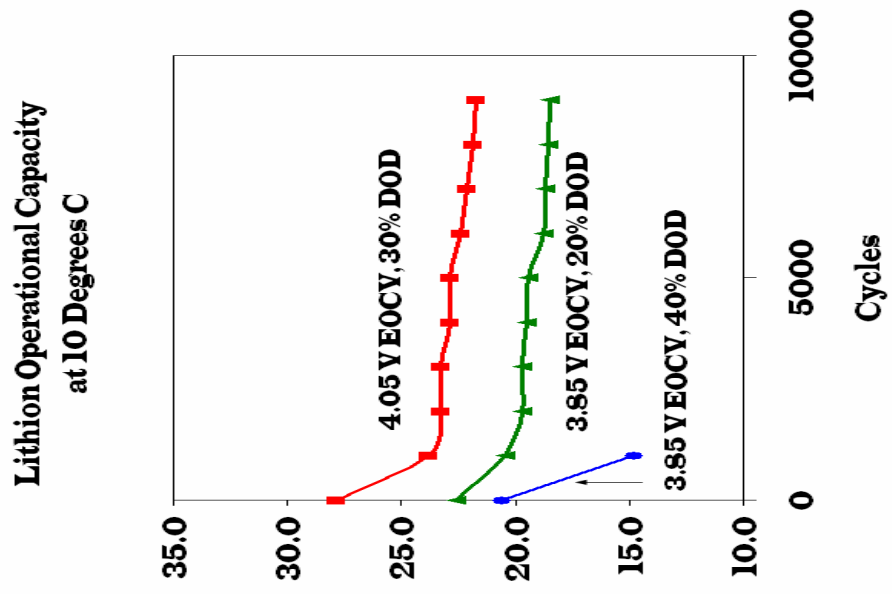
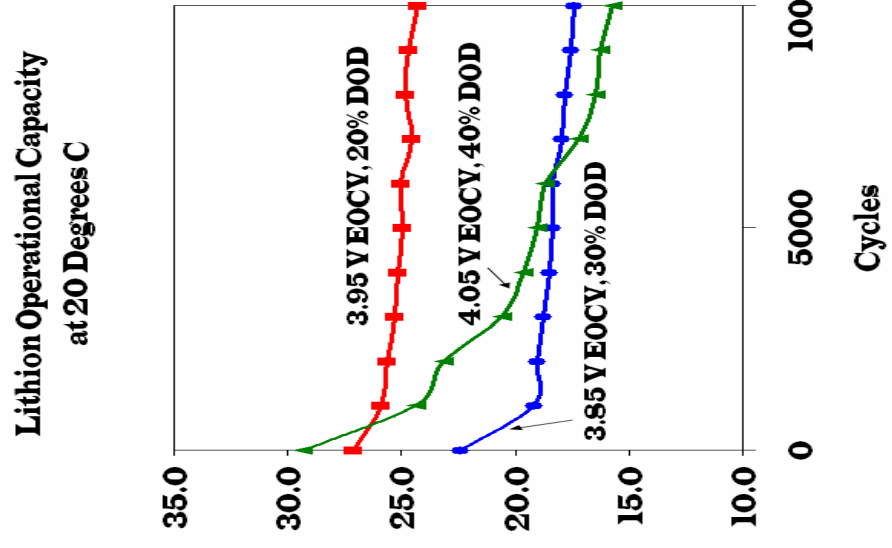
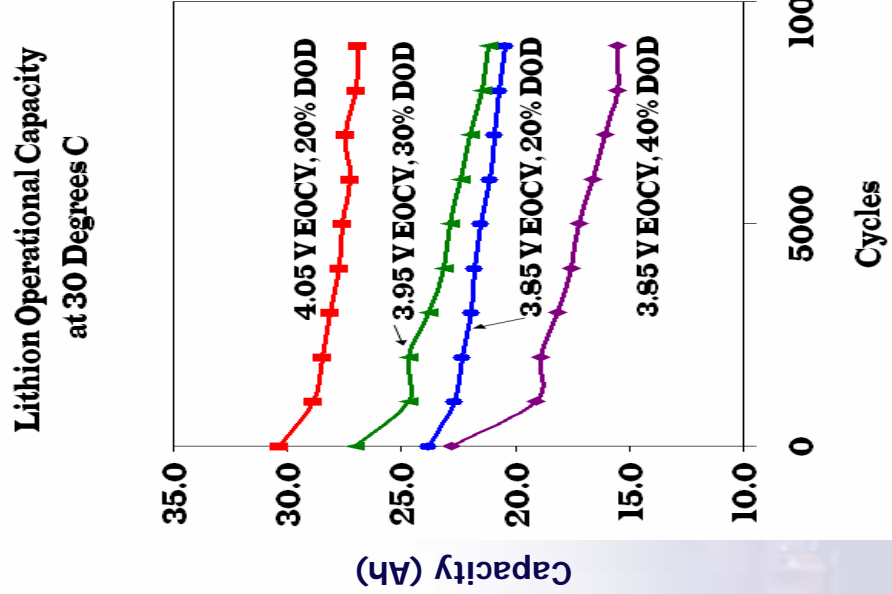


Soft Capacities at Test Conditions to 3.0 V versus Cycles as a Function of Temperature





Lithion Capacities at Test Conditions to 3.0 V versus Cycles as a Function of Temperature



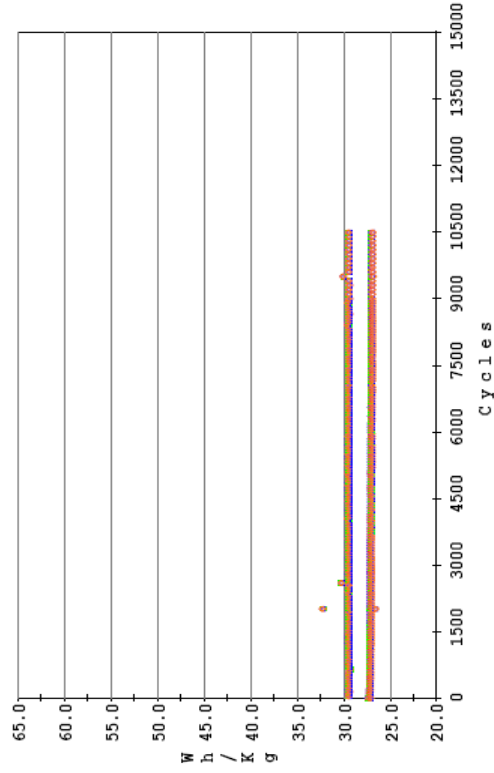


Comparison of Specific Energy and EODV versus Cycles Trends

Lithion Pack at Test Conditions 20 °C, 20% DOD and 3.95 V EOCV

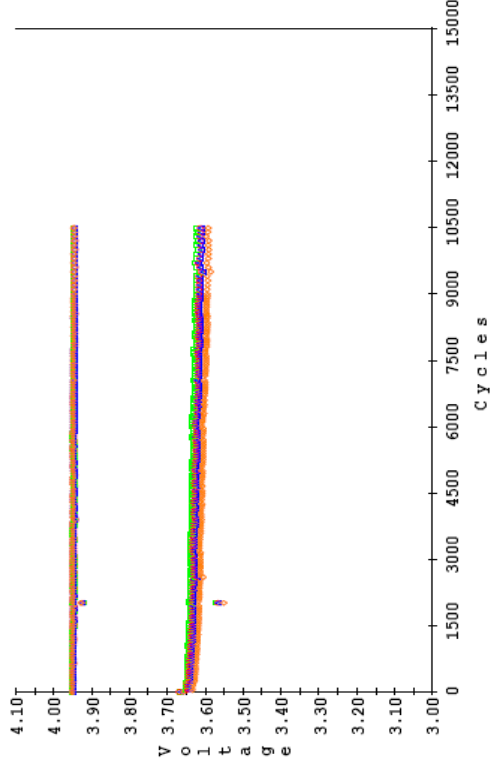
Specific Energy (Wh/kg)

LITHION PACK: H004YL 20 °C 20% DOD
Leo Life Cycling 3.95V Clamp 09-29-2004 - 09-01-2006
□ Cell 1 ○ Cell 2 ▲ Cell 3 ◇ Cell 4



EODV (V)

LITHION PACK: H004YL 20 DEG C 20% DOD
Leo Life Cycling 3.95V Clamp 09-29-2004 - 09-01-2006
□ Cell 1 ○ Cell 2 ▲ Cell 3 ◇ Cell 4





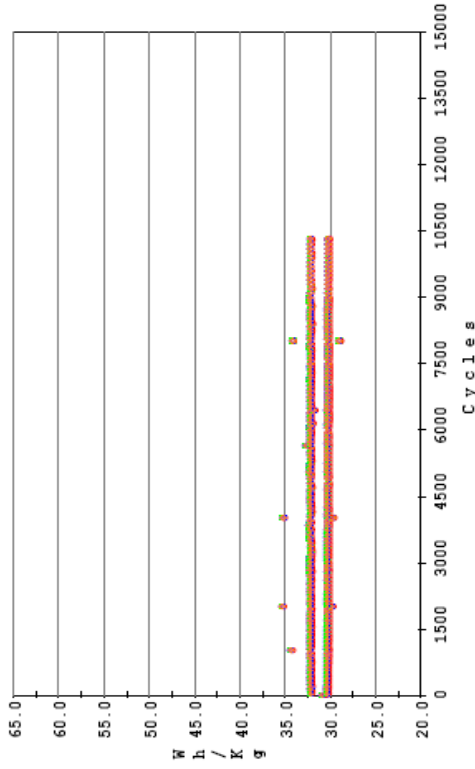
Comparison of Specific Energy and EODV versus Cycles Trends

Saftt Pack at Test Conditions 20 °C, 20% DOD and 3.95 V EOCV

Specific Energy (Wh/kg)

SAFTT PACK: H003SL 20 °C 20% DOD
 Leo Life Cycling 3.95V Clamp 09-29-2004 - 09-01-2006

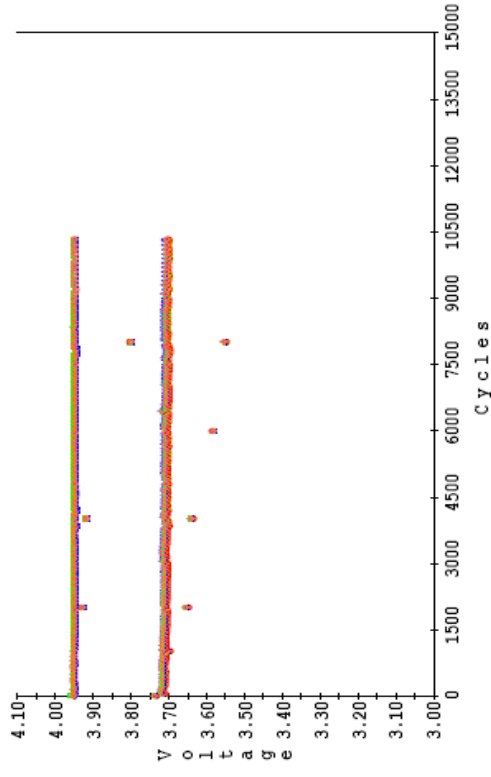
□ Cell 1 • Cell 2 ▲ Cell 3 ◆ Cell 4



EODV (V)

SAFTT PACK: H003SL 20 DEG C 20% DOD
 Leo Life Cycling 3.95V Clamp 09-29-2004 - 09-01-2006

□ Cell 1 • Cell 2 ▲ Cell 3 ◆ Cell 4



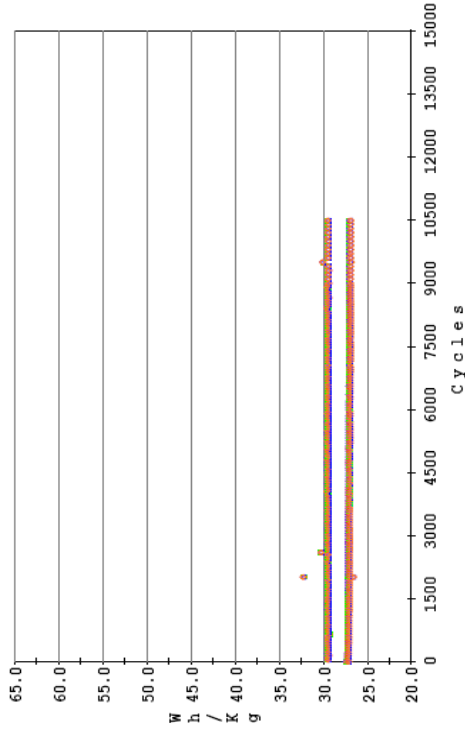


Comparison of Specific Energy versus Cycles for Lithion and Saft

Packs at Test Conditions 20 °C, 20% DOD and 3.95 V EOCV

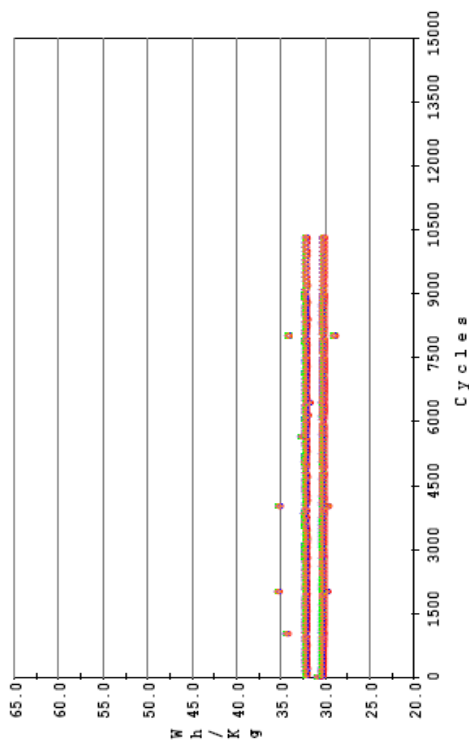
Lithion

LITHION PACK: H004YL 20°C 20% DOD
Leo Life Cycling 3.95V Clamp 09-29-2004 - 09-01-2006
□ Cell 1 ◊ Cell 2 ▲ Cell 3 ◊ Cell 4



Saft

SAFT PACK: H003SL 20°C 20% DOD
Leo Life Cycling 3.95V Clamp 09-29-2004 - 09-01-2006
□ Cell 1 ◊ Cell 2 ▲ Cell 3 ◊ Cell 4





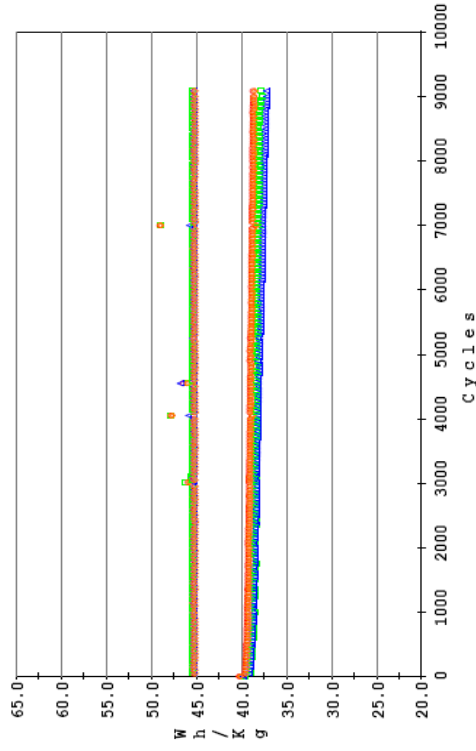
Comparison of Specific Energy and EODV versus Cycles Trends

Lithion Pack at Test Conditions 10 °C, 30% DOD and 4.05 V EOCV

Specific Energy (Wh/kg)

LITHION PACK: J010YL 10 °C 30% DOD
 Leo Life Cycling 4.05V Clamp 01-06-2005 - 09-01-2006

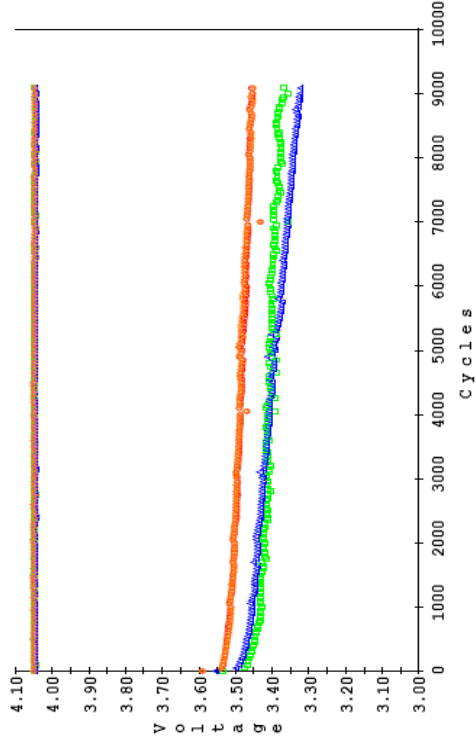
Cell 1 Cell 2 Cell 3 Cell 4



EODV (V)

LITHION PACK: J010YL 10 DEG C 30% DOD
 Leo Life Cycling 4.05V Clamp 01-06-2005 - 09-01-2006

Cell 1 Cell 2 Cell 3 Cell 4





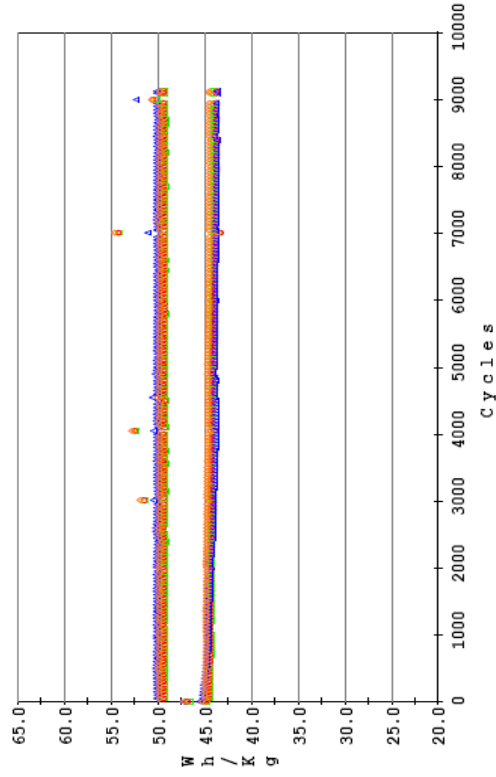
Comparison of Specific Energy and EODV versus Cycles Trends

Saft Pack at Test Conditions 10 °C, 30% DOD and 4.05 V EOCV

Specific Energy (Wh/kg)

SAFT PACK: J009SL 10 °C 30% DOD
 Leo Life Cycling 4.05V Clamp 01-06-2005 - 09-01-2006

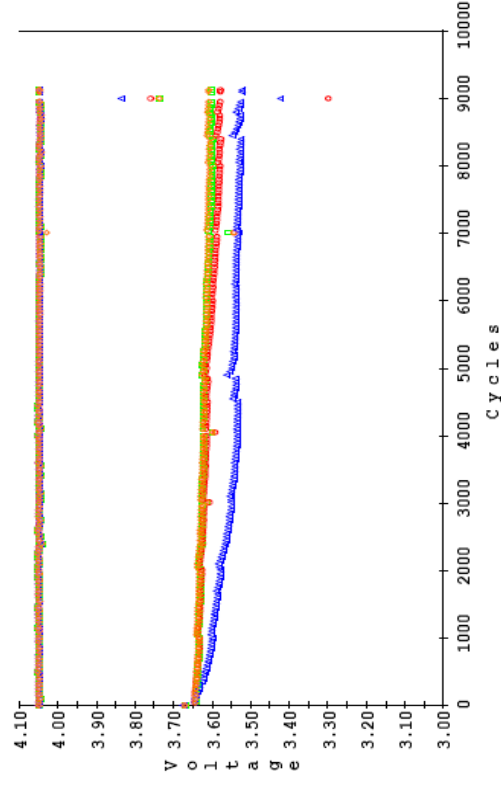
■ Cell 1 ● Cell 2 ▲ Cell 3 ◆ Cell 4



EODV (V)

SAFT PACK: J009SL 10 DEG C 30% DOD
 Leo Life Cycling 4.05V Clamp 01-06-2005 - 09-01-2006

■ Cell 1 ● Cell 2 ▲ Cell 3 ◆ Cell 4



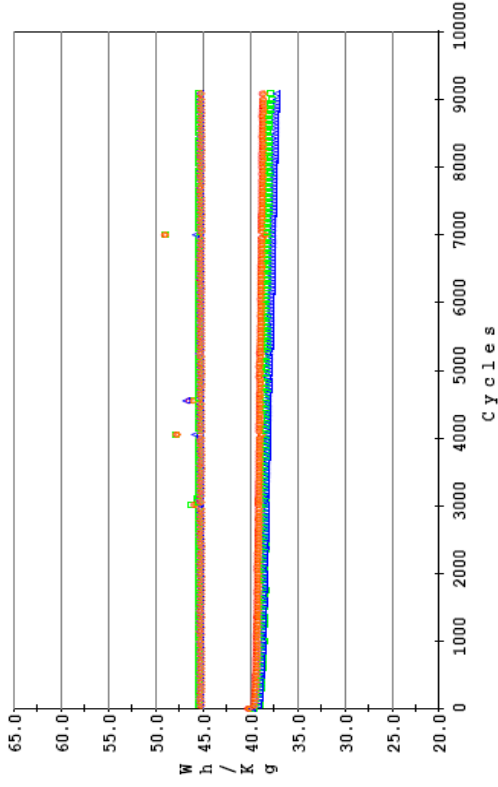


Comparison of Specific Energy versus Cycles for Lithion and Saft

Packs at Test Conditions 10 °C, 30% DOD and 4.05 V EOCV

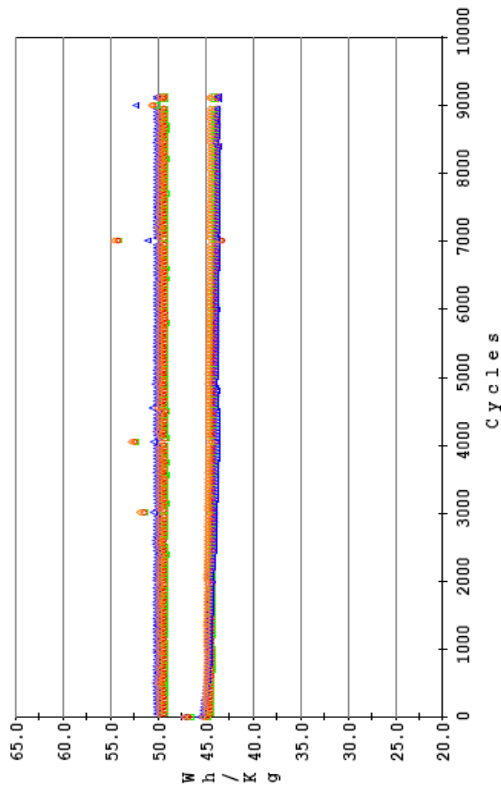
Lithion

LITHION PACK: J010YL 10 °C 30% DOD
Leo Life Cycling 4.05V Clamp 01-06-2005 - 09-01-2006
□ Cell 1 ● Cell 2 ▲ Cell 3 ◆ Cell 4



Saft

SAFT PACK: J009SL 10 °C 30% DOD
Leo Life Cycling 4.05V Clamp 01-06-2005 - 09-01-2006
□ Cell 1 ● Cell 2 ▲ Cell 3 ◆ Cell 4





Saft and Lithion Failure Summary

- A cell is considered failed if its EODV falls below 3.0 V during LEO cycling.
- Six cells have completed their life cycling by cycling to failure.
- All failures occurred in cells operating at the lowest EOCV and the highest DOD for each vendor.
 - Five of the six failures were in cells operating at the lowest temperature, 10 °C.
 - The sixth failed cell was operating at 30 °C.
 - Five of the cells were Lithion cells, including the cell cycling at 30 °C. The sixth cell was a Saft cell.
- Preliminary statistical models that incorporate early failure data are being built

Glenn Research Center



Saft and Lithion Failure Summary

Vendor	Temp (°C)	End-of-Charge Voltage/cell (V)	DoD (%)	Number of failures	Number of cycles achieved before failure
Lithion	10	3.85	40	4	900 (1), 3100 (3)
Lithion	30	3.85	40	1	6800
Saft	10	3.85	35	1	8400





Summary - Comparison of Saft and Lithion Results

- Saft and Lithion cells have achieved over 11,000 cycles each, equivalent to about 22 months in LEO.
- Saft cells generally have a higher end-of-discharge voltage (EODV) than Lithion cells operating at the same conditions.
- Saft cells have a lower EODV dispersion among cells operating at the same conditions than Lithion cells.
- For both vendors, when cells are operating at the highest DOD, the EODV of the cells varies more than the EODV for the cells operating at the lower DODs.
- As a cell's EODV gets lower and lower, operational capacity checks tend to have a more profound reconditioning effect on the cell.





Summary of MSA Cells and ABSL Modules

- MSA cells will begin life cycling in November 2006.
- Actual capacity determination, open circuit voltage stand, and capacity characterization at different temperatures is complete.
- ABSL modules have accumulated approximately 2800 cycles.
- Issues have arisen regarding test conditions.
- Test conditions are being reevaluated.

