Capacity Loss Studies on High
Capacity Li-ion Cells for the Orbiter
Advanced Hydraulic Power System

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• Performance Evaluation
  A. Rate Performance
  B. Internal Resistance
  C. Performance at Different Temperatures
• Safety Evaluation
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  B. Overdischarge
  C. External Short
  D. Simulated Internal Short
  E. Heat-to-Vent
  F. Vibration
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  H. Vent and Burst Pressure
Orbiter Hydrazine APU Description

Hydrazine APU Used Throughout the Shuttle Program to Power Hydraulic Systems
- Operates During Ascent, On-Orbit Flight Control System Checkout, and Descent
- Converts Chemical Hydrazine Fuel to Shaft Power to Drive a Hydraulic Pump
  - Catalytic Reaction Drives a High Speed Turbine; Speed Reduced to Hyd Pump via a Gearbox

Three Hydraulic Systems Distributed Throughout the Orbiter Power Hyd Actuators
- Variable Displacement, Piston Pump Converts APU Shaft Power to 3000 psi / 69 gpm Fluid Power (120 hp max)
- Hydraulic Power Distributed to 41 End Effectors
Objective: Determine Long Term Effects of “Storage” Temp & State of Charge (SOC) On Cell Capacity & Resistance

Description: Test Began in April, 2002 When 12 Cells Were Placed in Temperature Chambers and Stored Open Circuit at Various Temperatures and SOC (2 cells per condition). Testing Scheduled to End Sept 04 (~840 days)

Standard Discharge Cycles Performed Periodically to Trend Capacity Loss and Resistance Growth.

Capacity Loss Test Performed at NSWC in Crane, IN
# Test Matrix

<table>
<thead>
<tr>
<th>Cell Designation</th>
<th>Condition Description</th>
<th>Storage Temp</th>
<th>Storage SOC</th>
<th>Capacity Check</th>
</tr>
</thead>
<tbody>
<tr>
<td>112, 113</td>
<td>Vehicle Between Missions Cold</td>
<td>5°C (41°F)</td>
<td>5% - 10%</td>
<td>30 days</td>
</tr>
<tr>
<td>114, 115</td>
<td>Vehicle Between Missions Nom.</td>
<td>25°C (77°F)</td>
<td>5% - 10%</td>
<td>30 days</td>
</tr>
<tr>
<td>116, 117</td>
<td>Orbit Cold</td>
<td>25°C (77°F) 25°C (77°F)</td>
<td>5% - 10% 75% - 80%  (2.5 mo @ 5-10%, 15 days @ 75-80%, repeat)</td>
<td>0, 2.5, 3 mo (repeat)</td>
</tr>
<tr>
<td>118, 119</td>
<td>Orbit Nominal</td>
<td>25°C (77°F) 40°C (104°F)  (2.5 mo @ 25°C, 15 days @ 40°C, repeat)</td>
<td>5% - 10% 75% - 80%  (2.5 mo @ 5-10%, 15 days @ 75-80%, repeat)</td>
<td>0, 2.5, 3 mo (repeat)</td>
</tr>
<tr>
<td>120, 121</td>
<td>Orbit Hot</td>
<td>25°C (77°F) 65°C (149°F) (2.5 mo @ 25°C, 15 days @ 65°C, repeat)</td>
<td>5% - 10% 75% - 80%  (2.5 mo @ 5-10%, 15 days @ 75-80%, repeat)</td>
<td>0, 2.5, 3 mo (repeat)</td>
</tr>
<tr>
<td>122, 125</td>
<td>Post Landing Hot</td>
<td>25°C (77°F) 65°C (149°F) (2.5 mo @ 25°C, 1 day @ 65°C, repeat)</td>
<td>5% - 10% 75% - 80%  (2.95 mo @ 5-10%, 1 day @ 75-80%, repeat)</td>
<td>0, 2.95, 3 mo (repeat)</td>
</tr>
</tbody>
</table>
Standard Discharge Cycle

Standard Discharge Cycle Performed Periodically to Trend Capacity Loss and DC Resistance Growth.

Standard Discharge Cycle Consists of:

- Return to Room Temperature
- Discharge Fully
- Charge Fully to 4.1 VDC
- Discharge at C/2 Constant Current With 2.7 C Pulses at 60, 70, 80, 90 and 100 Minutes (95 amps constant with pulses to 513 amps)
- Upon Reaching 3.0 VDC, Decrease Current to C/10 and Continue Discharge Until Reaching 3.0 VDC
- Charge to Desired SOC
- Return to Desired Storage Temperature

Resistance Calculated Based on dV / dl for the 2.7 C Pulses

- Trends Reported in Following Pages are for the 100 minute Pulse
Comparison of Standard Capacity Cycles

The first vs last discharge curves for one of the two cells from each of the six storage groups was compared.
Comparison of Discharges Under Ground Storage Conditions at 5 °C & 10% SOC

Cell 112 - Discharge Cycle 1 & 21 (664 days) Comparison
(storage condition: 5 C & 10% SOC with capacity check every 30 days)

Red = First Cycle Current
Purple = Last Cycle Current
Blue = First Cycle Voltage
Green = Last Cycle Voltage

Time for Last Cycle Shifted 1 min Because Curves Lie On Top of Each Other

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Comparison of Discharges Under Conditions of Ground Storage at 25 °C & 10% SOC

Cell 114 - Discharge Cycle 1 & 21 (650 days) Comparison
(storage condition: 25 °C & 10% SOC with capacity check every 30 days)

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Comparison of Discharges Under Conditions of On-Orbit at 25 °C & 10%/80% SOC

Cell 116 - Discharge Cycle 1 & 15 (652 days) Comparison
(storage condition: 25 C & 10% SOC for 2.5 mo, 25 C & 80% SOC for 0.5 mo with capacity check at 2.5 & 3 mo)

- Red = First Cycle Current
- Purple = Last Cycle Current
- Blue = First Cycle Voltage
- Green = Last Cycle Voltage

Time for Last Cycle Shifted 1 min Because Peaks Lie On Top of Each Other

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Comparison of Discharges Under Conditions of On-Orbit at 25 °C/40 °C & 10%/80% SOC

Cell 118 - Discharge Cycle 1 & 15 (653 days) Comparison
(storage condition: 25 °C & 10% SOC for 2.5 mo, 40 °C & 80% SOC for 0.5 mo with capacity check at 2.5 & 3 mo)

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Comparison of Discharges Under Conditions of On-Orbit at 25 °C/65 °C & 10%/80% SOC

Cell 120 - Discharge Cycle 1 & 15 (653 days) Comparison
(storage condition: 25 °C & 10% SOC for 2.5 mo, 65 °C & 80% SOC for 0.5 mo with capacity check at 2.5 & 3 mo)

- Red = First Cycle Current
- Purple = Last Cycle Current
- Blue = First Cycle Voltage
- Green = Last Cycle Voltage

Time for Last Cycle Shifted 1 min Because Peaks Lie On Top of Each Other

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Comparison of Discharges Under Conditions of Post Landing at 25 °C/65 °C & 10%/80% SOC

Cell 122 - Discharge Cycle 1 & 15 (651 days) Comparison
(storage condition: 25 C & 10% SOC for 2.95 mo, 65 C & 80% SOC for 0.05 mo with capacity check at 2.95 & 3 mo)

- Red = First Cycle Current
- Purple = Last Cycle Current
- Blue = First Cycle Voltage
- Green = Last Cycle Voltage

Time for Last Cycle Shifted 1 min Because Peaks Lie On Top of Each Other

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Capacity Loss Data

Quantity of Data Points & Differing Starting Points Make These Results for Absolute Capacity Difficult to Interpret

Crane Calendar Loss Test - Capacity

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Resistance Growth

Quantity of Data Points & Differing Starting Points Make These Results for Absolute Resistance Difficult to Interpret

Crane Calendar Loss Test - Resistance

![Graph showing Cell Resistance over Time]

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Capacity Loss – Ground Storage Conditions

Melco 190 Ah Cell Long Term Capacity Loss (Ground)

Cell Capacity Loss - pct loss from start

Time - days

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Resistance Growth – Ground Storage Conditions

Melco 190 Ah Cell Long Term Resistance Growth (Ground)

Time - days

Cell Resistance Growth - % Increase from start

2SC & 10% SOC (114 & 115)

5C & 10% SOC (112 & 113)

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Capacity Loss – On-Orbit Storage Conditions

Melco 190 Ah Cell Long Term Capacity Loss (Orbit)

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Resistance Growth – On-Orbit Storage Conditions

Melco 190 Ah Cell Long Term Resistance Growth (Orbit)
Resistance During Standard Capacity Cycle Profile

(cells with most benign and most extreme storage conditions)
Mission Resistance – Ground Cold Storage

Cell With Most Benign Storage Condition Shows Upward Shifting Curves

Cell 112 Resistance During a Discharge Cycle

![Graph showing resistance over time with cycles indicated]

- Trend unknown between because no data points
- Calendar & cycle time progressing

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Mission Resistance – Orbit Hot Storage

Cell With Most Extreme Storage Condition Shows Upward Shifting Curves and Rise at End

Cell 121 Resistance During a Discharge Cycle

trend unknown between because no data points
calendar & cycle time progressing

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Summary of Average Capacity Loss

Average Capacity Loss - JSB 190 Ah Calendar Loss Test at Crane (after 664 days)

Storage Condition

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Summary of Average Resistance Growth

Average Resistance Growth - JSB 190 Ah Calendar Loss Test at Crane (after 664 days)

[Graph showing resistance growth for different cells with various storage conditions]
Results for 190 Ah Cycle Test Conducted at Schlumberger in Rosharon, TX

Discharge Capacity

Charge Capacity

Internal Resistance (ohms)

Capacity (Ah)

Cycle Number

Cycle Number

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Summary of Results

- Results Excellent for the Orbiter AHPS Application
- Mostly Expected Trends with Temperature and State of Charge
  - Higher Temp and/or Higher SOC Produce More Cell Degradation
- Cell Capacity Loss Characteristics are Excellent
- Cell Resistance Growth Is Greater Than Capacity Loss (% change)
  - However, Results are Really Magnified Because of the Incredibly Low Initial Cell Resistances
- Comparison with Sizing Model Used to Reduce Needed Cell Size for AHPS Application from 190 Ah to 120 Ah
  - Measured Capacity Loss is Less Than Model
  - Measured Resistance Growth is More than Model
  - Overall, 120 Ah Sizing Provides Adequate Margin for the AHPS Application 8 Mission, 30 Cycle, 3 year Requirement

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Acknowledgment

NSWC in Crane, IN.