International Space Station
Lithium-Ion Battery Start-Up
Space Power Workshop
April 25, 2017

Penni J. Dalton, NASA Glenn Research Center
Tim North, The Boeing Company
Ebony Bowens, The Boeing Company
Sonia Balcer, Aerojet Rocketdyne
ISS Li-Ion Battery - Outline

• Configuration of Existing ISS Electric Power System
• Final Flight Adapter Plate and Battery Design
• Launch and Installation
• Battery Charge Control and LEO Cycle Test Data
• On-Orbit cycling data
• Cell and ORU Life Test
ISS Configuration - Battery Locations

Batteries are located in the 4 Integrated Equipment Assemblies (IEAs)

2 Power Channels per IEA

8 Power Channels total

6 Ni-H$_2$ ORUs per channel – 48 total

1 Li-Ion and 1 Adapter Plate to replace
2 Ni-H$_2$ – 24 total Li-ion batteries
ISS Configuration - EPS Schematic

Electrical Power Channel – 1 of 8

Note: 2-Battery ORUs will be replaced by 1 Li-Ion Battery and an Adapter Plate

EPS:: Electric Power System
BCDU: Battery Charge / Discharge Unit
DCSU: DC Switching Unit
DDCU: DC-to-DC Converter Unit
MBSU: Main Bus Switching Units
ISS Upgrade to Li-Ion

**Ni-H₂**
(76 cells in series)

- **BCDU**: Battery Charge / Discharge Unit
- **Ni-H₂**: Nickel-Hydrogen Battery
- **Commands & Data**: Data flow between BCDU and Ni-H₂ Cells
- **Ni-H₂ Cells**: 76 cells in series
- **Battery A**: Existing
- **Battery B**: Existing

**Li-Ion**
(30 cells in series)

- **BCDU**: Battery Charge / Discharge Unit
- **Li-Ion**: Lithium-Ion Battery
- **Commands & Data**: Data flow between BCDU and Li-Ion Cells
- **Li-Ion Cells**: 30 cells in series
- **Battery**: Existing
- **Adapter Plate**: New
- **Data Cable**: Connection to Adapter Plate

**Notes**
- **BIU**: Battery Interface Unit
- **BSCCM**: Battery Signal Conditioning and Control Module

**Legend**
- **Main Power Path**: Positive to Positive, Negative to Negative
- **Commands & Data**:
  - **Existing**
  - **New**
ISS Li-Ion Orbital Replacement Units
(Direct drop in replacement for Ni-H₂)

Heater Matt
Heater Plate Assembly

P4 Connector
(stowed for launch)

EVA
Hand Hold

P1 & P2
Connectors

J3 Test Connector

J4
Connector

Adapter Plate ORU

Dimensions (LxWxH): ~ 41” x 36” x 15”
Spec Weight: 85 Lbs

Li-Ion Battery ORU

Dimensions (LxWxH): ~ 41” x 37” x 21”
Spec Weight: 435 Lbs
ISS Li-Ion Flight Battery Status

- 6 Flight Li-Ion Adapter Plates integrated with Exposed Pallet in Japan, Tomioka: April 2016
- 6 Flight Li-Ion Batteries integrated with Exposed Pallet in Japan, Tanegashima: May 2016
- Final charge to 4.1V: May-June 2016
- Launch on HTV6: December 9, 2016
  - Each IEA will have 3 Li-Ion ORUs and 3 Adapter Plate ORUs
- Installation and start-up on ISS:
  S4 3A channel – Jan. 6, 2017
  S4 1A channel, Jan. 13, 2017
Docking of HTV6 to ISS

HTV Approach to ISS

- Launch Date December 9, 2016
- EP (Exposed Pallet) Captured and Attached to POA 12/13/2016
- Installation and startup (next slides)
Removal of Exposed Pallet with Li-Ion ORUs

- 12/13/2016 After docking, robotic removal of EP with Li-Ion ORUs
Moving the Li-Ion ORUs

- 12/13/2016 After ISS docking, EP taken out of HTV6
- EP moved to ISS truss for Battery installation
Robotic Installation of Li-Ion Battery ORU

- **S4 3A Batteries**
  - Robotically installed 12/31–1/2/2017
  - EVA and start up 1/6/2017

- **S4 1A Batteries**
  - Robotically installed 1/8–1/12/2017
  - EVA and start up 1/13/2017

Li-Ion Battery ORU

Robotic Arm (Dextre)
EVA Adapter Plate Installation

- S4 3A EVA and start up 1/6/2017
- S4 1A EVA and start up 1/13/2017
Robotic Disposal of Exposed Pallet with 9 Ni-H$_2$ ORUs

- 1/22/2017 Robotic arm moving EP with 9 Ni-H$_2$ ORUs towards HTV6
Robotic Disposal of Exposed Pallet with 9 Ni-H₂ ORUs

- 1/22/2017  Robotic arm inserting EP with 9 Ni-H₂ ORUs back into HTV6
- 1/27/2017  Undocking
- 2/5/2017   Reentry
Li-Ion Battery Status

• Starting January 13, 2017, S4 Channels 3A and 1A are being operated using only Li-Ion Batteries
  • Batteries are performing well – capacity tests at EOCV of 3.95 V
    • 3A: 109.3, 110.3, 110.9 Ah (see page 18)
    • 1A: 114.0, 110.3, 112.3 Ah
  • Minor operational observations / forward work
    • Battery Charge Discharge Unit advisory message – upper Voltage Limit of 122 V exceeded (Limit to be updated to 124 V)
    • Occasional switchovers of redundant heaters (A to B, B to A) (Persistence time to be updated)
    • State of Charge calculation to be updated to increase accuracy
    • Adjustments to Charge Profile to be evaluated

• 17 of 27 Li-Ion batteries have been built and delivered
  • 6 on orbit, 11 in cold storage at KSC
• 16 of 25 Adapter Plates have been built and delivered
  • 6 on orbit, 10 in storage at KSC

• Future Launches
  • Next Lithium-Ion Battery launch on HTV7, NET Feb. 2018
  • Subsequent launches on HTV8- 2019, HTV9- 2020
ISS Li-Ion Charge Control and Cycling

- Li-Ion charge current profile is based on cell voltages
- Cell bypass/balancing at EOCV every orbit
- EOCV ground command-able

### Charge Current Profile

<table>
<thead>
<tr>
<th>Point</th>
<th>Highest of the Cell Terminal Voltages</th>
<th>Charge Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>EOCV + 19mV</td>
<td>55</td>
</tr>
<tr>
<td>Point 2</td>
<td>EOCV + 19mV</td>
<td>49</td>
</tr>
<tr>
<td>Point 3</td>
<td>EOCV + 18mV</td>
<td>44</td>
</tr>
<tr>
<td>Point 4</td>
<td>EOCV + 17mV</td>
<td>39</td>
</tr>
<tr>
<td>Point 5</td>
<td>EOCV + 16mV</td>
<td>36</td>
</tr>
<tr>
<td>Point 6</td>
<td>EOCV + 15mV</td>
<td>33</td>
</tr>
<tr>
<td>Point 7</td>
<td>EOCV + 14mV</td>
<td>30</td>
</tr>
<tr>
<td>Point 8</td>
<td>EOCV + 13mV</td>
<td>26</td>
</tr>
<tr>
<td>Point 9</td>
<td>EOCV + 12mV</td>
<td>22</td>
</tr>
<tr>
<td>Point 10</td>
<td>EOCV + 11mV</td>
<td>19</td>
</tr>
<tr>
<td>Point 11</td>
<td>EOCV + 10mV</td>
<td>16</td>
</tr>
<tr>
<td>Point 12</td>
<td>EOCV + 9mV</td>
<td>13</td>
</tr>
<tr>
<td>Point 13</td>
<td>EOCV + 8mV</td>
<td>10</td>
</tr>
<tr>
<td>Point 14</td>
<td>EOCV + 7mV</td>
<td>7</td>
</tr>
<tr>
<td>Point 15</td>
<td>EOCV + 6mV</td>
<td>4</td>
</tr>
<tr>
<td>Point 16</td>
<td>not applicable</td>
<td>1</td>
</tr>
</tbody>
</table>

Data for Battery Channel 3A after ~30 days operation
ISS Li-Ion Charge Control and Cycling

Battery 3A2 (Typical) Capacity Test

- ORU Voltage
- Cell Voltages
- ORU Current
Life Test Program

• Cell Life Testing performed at Crane Lab and NASA-GRC
Life Test Program

Li-Ion Battery ORU Life Testing at Aerojet Rocketdyne Voltage Retention Test Data

Week 16 Test error resulted in ~ 1.15 A-Hr discharge

Week 22 Chamber Condenser failure resulted in temperature change

Chamber Temperature at 78 °F (first 21 weeks)

70 to 73 °F (week 23 on)

Ongoing Series, Life Test Apr. 2017
ISS Li-Ion Battery Future Plans

• Data analysis for NESC (NASA Engineering & Safety Center) Thermal runaway propagation test performed October 2016 at the White Sands Test Facility

• Launch of remaining Li-Ion Batteries and Adapter Plates in 2018, 2019, 2020 to provide a full complement on ISS

➤ First six batteries (2 power channels) operating successfully on orbit
In Closing

• Questions?
Backup Materials

• Installation Robotic and EVA sequence
Robotic Operations

3A Robotic: 
(12/31/2016 – 1/3/2017)
1A Robotic: 
(1/8/2017 – 1/12/2017)

<table>
<thead>
<tr>
<th>Shift</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Ni-H₂: 5 &gt; Z</td>
</tr>
<tr>
<td>1B</td>
<td>Ni-H₂: 6 &gt; Y</td>
</tr>
<tr>
<td>2A</td>
<td>Li-Ion: B &gt; 5</td>
</tr>
<tr>
<td>2B</td>
<td>Ni-H₂: 1 &gt; X</td>
</tr>
<tr>
<td>3A</td>
<td>Li-Ion: A &gt; 1</td>
</tr>
<tr>
<td>3B</td>
<td>Ni-H₂: 3 &gt; EOTP</td>
</tr>
<tr>
<td>4A</td>
<td>Li-Ion: C &gt; 3</td>
</tr>
<tr>
<td>4B</td>
<td>ROST: 1/5</td>
</tr>
</tbody>
</table>
EVA Operations

3A EVA:
(1/6/2017 & 1/13/2017)
1A EVA:
(1/13/2017)

Adapter Plate
A > 6

Ni-H₂
4 > AP 6

Adapter Plate
B > 4

Ni-H₂
2 > AP 4

Adapter Plate
C > 2

Release
1A IEA H1 Slot 2