International Space Station
Lithium-Ion Battery

NASA Aerospace Battery Workshop
November 15, 2016

Penny J. Dalton, NASA Glenn Research Center
Eugene Schwanbeck, NASA Johnson Space Center
Tim North, The Boeing Company
Sonia Balcer, Aerojet Rocketdyne
ISS Li-Ion Battery - Outline

- Configuration of Existing ISS Electric Power System
- Timeline of Li-Ion Battery Development
- Battery Design Drivers
- Technical Definition Studies
- Cell Selection
- Safety Features
- Final Flight Adapter Plate and Battery Design
- Battery Charge Control and LEO Cycle Test Data
- Cell and ORU Life Test
- Current Status
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-H₂ ORUs per channel – 48 total

1 Li-Ion and 1 Adapter Plate to replace
2 Ni-H₂ – 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 Li-Ion Battery Project Overview

- Battery ORU (Orbital Replacement Unit)
  - Battery ORU Design and Manufacture
  - Baseplate Design and Manufacture
  - Enclosure Design (HOU) and Manufacture (AASC)
  - Li-Ion Battery Cells (GS Yuasa)
  - Charge Control Electronics Design and Manufacture
- On-Orbit Adapter Plate (Atec)
- Flight Support Equipment (FSE) Interface Hardware
- Li-Ion Battery Status/Charging Unit (SCU)
- Software Updates (PVCA, PCS, PMCA, and CCS)
- Testing
  - ORU Verification and Qualification Testing
  - Battery Cell Qualification and Acceptance Testing
  - Battery ORU Life Testing
  - ISS Systems Integration Testing
  - Battery Cell Safety Characterization/Abuse Testing and Battery Cell Life Testing
  - Post Delivery ORU Freezer/Refrigerator Storage
- Automated Test Equipment Design and Manufacture

Color Key (Scope):
- NASA
- Boeing
- ORU Supplier AR (Aerojet Rocketdyne)
- Joint Boeing/AR
Timeline of ISS Li-Ion Development

• **2009-2010** – Preliminary risk and feasibility studies

• **December 2011** - ISS Program Authority To Proceed with design, development and the fabrication of 27 Li-Ion ORUs and 25 on-orbit Adapter Plate ORUs

• **Jan-Jun 2012** - Cell Safety Testing and Cell Qualification

• **July 2012** - Final cell down-select

• **December 2012** - System Preliminary Design Review

• **November 2013** - System Critical Design Review

• **March 2016** - First flight Li-Ion battery delivered to Kennedy Space Center for shipment to Tanegashima, Japan
1 Li-ion battery ORUs replaces 2 Ni-H$_2$ ORUs
- Li-ion ~15 kWh vs. Ni-H$_2$ ~4 kWh each

Launch on Japanese HTV

6 year battery storage life requirement

10 year/60,000 cycle life target (minimum 48 A-hr capacity at end of life)
- ORU will have cell balancing circuitry
- ORU will have adjustable End of Charge Voltage (EOCV)

Maximum battery ORU weight ~430 lbs

Non-operating temperature range (Launch to Activation): -40 to +60 °C

No changes to existing IEA interfaces and hardware
- Use existing mounting, attachment, electrical & data connectors
- Use existing Charge/Discharge Units and Thermal control systems
ISS Upgrade to Li-Ion

**Ni-H₂**
(76 cells in series)

- **BCDU**: Battery Charge / Discharge Unit
- **Ni-H₂ Cells**: Nickel-Hydrogen Cells
- **Battery A**
- **Battery B**
- **BSxCCM**: Battery Signal Conditioning and Control Module

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

- **BCDU**: Battery Charge / Discharge Unit
- **Li-Ion Cells**: Lithium-Ion Cells
- **Battery**
- **BIU**: Battery Interface Unit
- **Adapter Plate**
- **Data Cable**

**Commands & Data**

**Main Power Path**

Existing

New
ISS Li-Ion Technical Definition Studies

NASA Down Select to 4 cell candidates (April 2010)


Battery Mounting/ MOD Kit Feasibility Report (includes ORU Max Weight Assessment) (May 2010 – Sept 2010)


NASA Safety Risk Mitigation Activity (Jan 2009 – Sept 2010)


(Sparing Analysis Report (May 2010 – Sept 2010)

NASA Production Line Audits (May 2010 – Aug 2010)

NASA Risk Mitigation Safety Report (Nov 2010)

Battery ORU Specification and SOW Development (start Sept 2010)

Cell Selection NAR (Sept 2010)

6 cell designs

4 cell designs

2 cell designs
ISS Li-Ion Cell Final Down-Select

- Two designs taken through qualification, with down-selection made prior to EM build

GS Yuasa 134 A-hr cells

- Li Cobalt Oxide / Carbon Graphite
- Wound elliptical prismatic electrode
- Internal Fusible link
- Aluminum Case, 50 x 130 x 263 mm
- Spec Mass: 3530 grams (~7.8 lb)
ISS Li-Ion Battery Safety Features

Battery-Level Safety Features

- 2 independent controls vs. thermal runaway (2 fault tolerant)
- Voltage and temperature monitoring of all 30 cells
- Circuit protection/fault isolation at the individual cell level for both high/low voltage and high temperature
- Physical separation between cell pairs and 10 packs
  - Thermal radiant barriers between cell pairs
- Controlled direction of cell vents - prevent damage to cold plate, adjacent cells and IEA hardware
  - ORU pressure relief/flame trap to prevent ORU over-pressurization but contain flame in the event of a cell vent
- MMOD shielding in ORU and empty ORU slot
- Dead face device to remove power from output connector during ground or EVA handling
- Non propagation of failures beyond Battery ORU
Safety Features - MMOD Shielding

**MMOD Shielding**

- **MMOD test setup**
- **Ballistic Limit Testing**
- **Over Match - Penetration testing**
  - 10 mm 2017-T4 Aluminum Sphere @ 6.86 km/s
- **Overcharge Containment Testing**

Note: Existing Ni-H₂ does not have MMOD protection
Safety Features - Radiant Heat Barriers

- ORU Layout – 3 Cell “10-Packs” and 12 Radiant Barriers

Radiant Heat Barrier (12 per ORU)
- Higher margin against thermal runaway propagation
- 1 barrier between each cell pair
- Reflects 787 reach-back safety additions
Cell-Level Safety Features and Controls

- Manufacturing Process controls include 100% materials screening and chemical analysis plus annual configuration/production line audits
- 100% cell acceptance testing
  - Cell Matching performed based on ATP characteristics
- 2% of cells in each lot in simulated LEO life cycle testing
- 1% of cells in each lot undergo 100, 100% DOD cycles, followed by DPA
- Cell vent before burst and directional vent away from base plate and adjacent cells
- Individual cell fusing (internal fusible link)
- Shutdown separators between electrode windings
- Case neutral and electrically insulated from ORU structure
ISS Li-Ion Orbital Replacement Units

Heater Matt
Heater Plate Assembly

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 Charge Control and Cycling

- Li-Ion charge current profile based on cell voltages
- Cell bypass/balancing at EOCV every orbit
- EOCV is 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>1</td>
<td>EOCV + 19mV</td>
<td>55</td>
</tr>
<tr>
<td>2</td>
<td>EOCV + 19mV</td>
<td>49</td>
</tr>
<tr>
<td>3</td>
<td>EOCV + 18mV</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>EOCV + 17mV</td>
<td>39</td>
</tr>
<tr>
<td>5</td>
<td>EOCV + 16mV</td>
<td>36</td>
</tr>
<tr>
<td>6</td>
<td>EOCV + 15mV</td>
<td>33</td>
</tr>
<tr>
<td>7</td>
<td>EOCV + 14mV</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>EOCV + 13mV</td>
<td>26</td>
</tr>
<tr>
<td>9</td>
<td>EOCV + 12mV</td>
<td>22</td>
</tr>
<tr>
<td>10</td>
<td>EOCV + 11mV</td>
<td>19</td>
</tr>
<tr>
<td>11</td>
<td>EOCV + 10mV</td>
<td>16</td>
</tr>
<tr>
<td>12</td>
<td>EOCV + 9mV</td>
<td>13</td>
</tr>
<tr>
<td>13</td>
<td>EOCV + 8mV</td>
<td>10</td>
</tr>
<tr>
<td>14</td>
<td>EOCV + 7mV</td>
<td>7</td>
</tr>
<tr>
<td>15</td>
<td>EOCV + 6mV</td>
<td>4</td>
</tr>
<tr>
<td>16</td>
<td>not applicable</td>
<td>1</td>
</tr>
</tbody>
</table>

### Nominal Orbit Cell Voltages

![Nominal Orbit Cell Voltages Chart](image)

### Nominal Orbit Current

![Nominal Orbit Current Chart](image)
Life Test Program

• Cell Life Testing performed at Crane and at GRC
Life Test Program

• ORU Life Testing at Aerojet Rocketdyne

Li-Ion Battery ORU Life Test 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)

<table>
<thead>
<tr>
<th>Elapsed Weeks</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.960</td>
</tr>
<tr>
<td>1</td>
<td>3.961</td>
</tr>
<tr>
<td>2</td>
<td>3.962</td>
</tr>
<tr>
<td>3</td>
<td>3.963</td>
</tr>
<tr>
<td>4</td>
<td>3.964</td>
</tr>
<tr>
<td>5</td>
<td>3.965</td>
</tr>
<tr>
<td>6</td>
<td>3.966</td>
</tr>
<tr>
<td>7</td>
<td>3.967</td>
</tr>
<tr>
<td>8</td>
<td>3.968</td>
</tr>
<tr>
<td>9</td>
<td>3.969</td>
</tr>
<tr>
<td>10</td>
<td>3.970</td>
</tr>
<tr>
<td>11</td>
<td>3.971</td>
</tr>
<tr>
<td>12</td>
<td>3.972</td>
</tr>
<tr>
<td>13</td>
<td>3.973</td>
</tr>
<tr>
<td>14</td>
<td>3.974</td>
</tr>
<tr>
<td>15</td>
<td>3.975</td>
</tr>
<tr>
<td>16</td>
<td>3.976</td>
</tr>
<tr>
<td>17</td>
<td>3.977</td>
</tr>
<tr>
<td>18</td>
<td>3.978</td>
</tr>
<tr>
<td>19</td>
<td>3.979</td>
</tr>
<tr>
<td>20</td>
<td>3.980</td>
</tr>
<tr>
<td>21</td>
<td>3.981</td>
</tr>
<tr>
<td>22</td>
<td>3.982</td>
</tr>
<tr>
<td>23</td>
<td>3.983</td>
</tr>
<tr>
<td>24</td>
<td>3.984</td>
</tr>
<tr>
<td>25</td>
<td>3.985</td>
</tr>
<tr>
<td>26</td>
<td>3.986</td>
</tr>
</tbody>
</table>

Chamber Temperature at 73 °F (week 23 on)

<table>
<thead>
<tr>
<th>Elapsed Weeks</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.960</td>
</tr>
<tr>
<td>1</td>
<td>3.961</td>
</tr>
<tr>
<td>2</td>
<td>3.962</td>
</tr>
<tr>
<td>3</td>
<td>3.963</td>
</tr>
<tr>
<td>4</td>
<td>3.964</td>
</tr>
<tr>
<td>5</td>
<td>3.965</td>
</tr>
<tr>
<td>6</td>
<td>3.966</td>
</tr>
<tr>
<td>7</td>
<td>3.967</td>
</tr>
<tr>
<td>8</td>
<td>3.968</td>
</tr>
<tr>
<td>9</td>
<td>3.969</td>
</tr>
<tr>
<td>10</td>
<td>3.970</td>
</tr>
<tr>
<td>11</td>
<td>3.971</td>
</tr>
<tr>
<td>12</td>
<td>3.972</td>
</tr>
<tr>
<td>13</td>
<td>3.973</td>
</tr>
<tr>
<td>14</td>
<td>3.974</td>
</tr>
<tr>
<td>15</td>
<td>3.975</td>
</tr>
<tr>
<td>16</td>
<td>3.976</td>
</tr>
<tr>
<td>17</td>
<td>3.977</td>
</tr>
<tr>
<td>18</td>
<td>3.978</td>
</tr>
<tr>
<td>19</td>
<td>3.979</td>
</tr>
<tr>
<td>20</td>
<td>3.980</td>
</tr>
<tr>
<td>21</td>
<td>3.981</td>
</tr>
<tr>
<td>22</td>
<td>3.982</td>
</tr>
<tr>
<td>23</td>
<td>3.983</td>
</tr>
<tr>
<td>24</td>
<td>3.984</td>
</tr>
<tr>
<td>25</td>
<td>3.985</td>
</tr>
</tbody>
</table>

Ongoing
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 HTV: NET December 2016
  - Each IEA will have 3 Li-Ion ORUs and 3 Adapter Plate ORUs
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 six Li-Ion Batteries and six Adapter Plates in 2017, 2018, 2019 to provide a full complement on ISS

➢ Ready for successful and safe operation
In Closing

• Acknowledgements

• Questions?