International Space Station Li-ion Battery Change-out Experience Through 2021

SPACE POWER WORKSHOP

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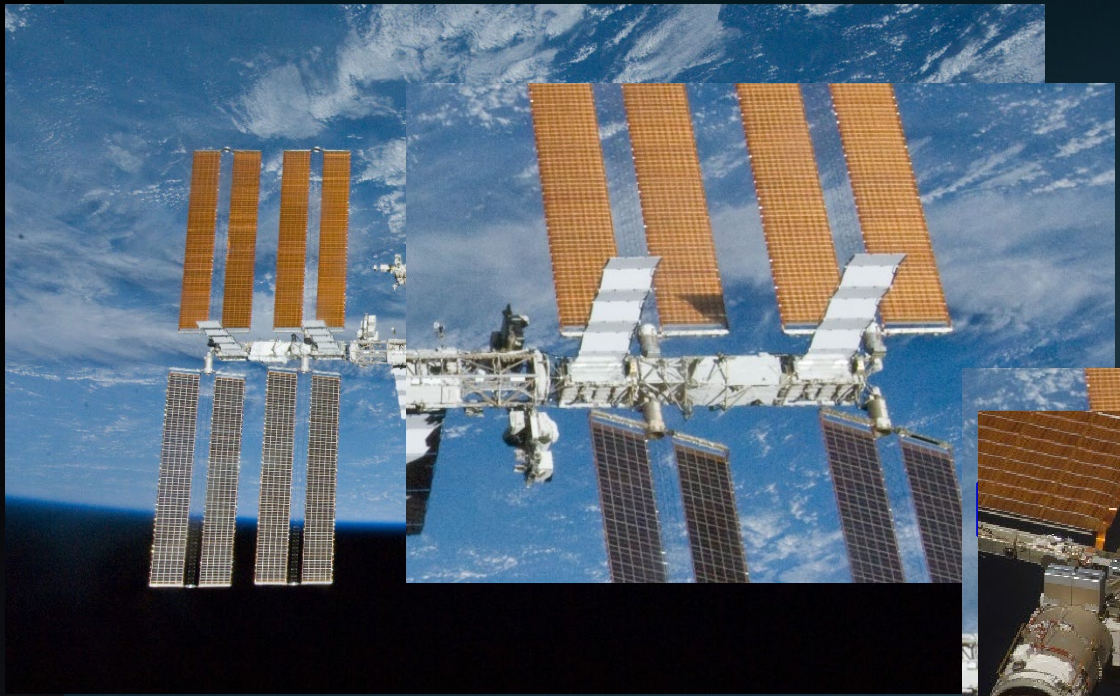
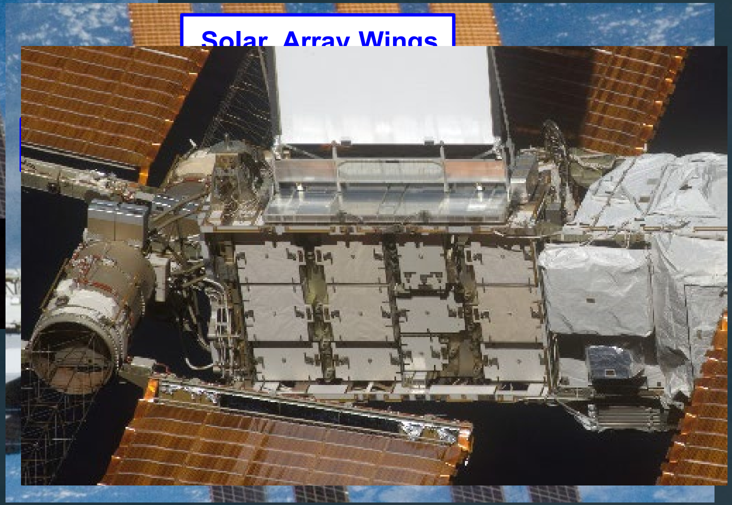
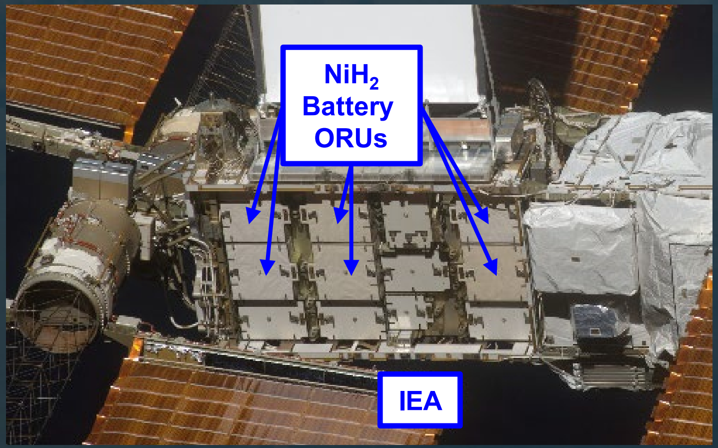
ISS Configuration - Battery Locations



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



8 Power Channels total



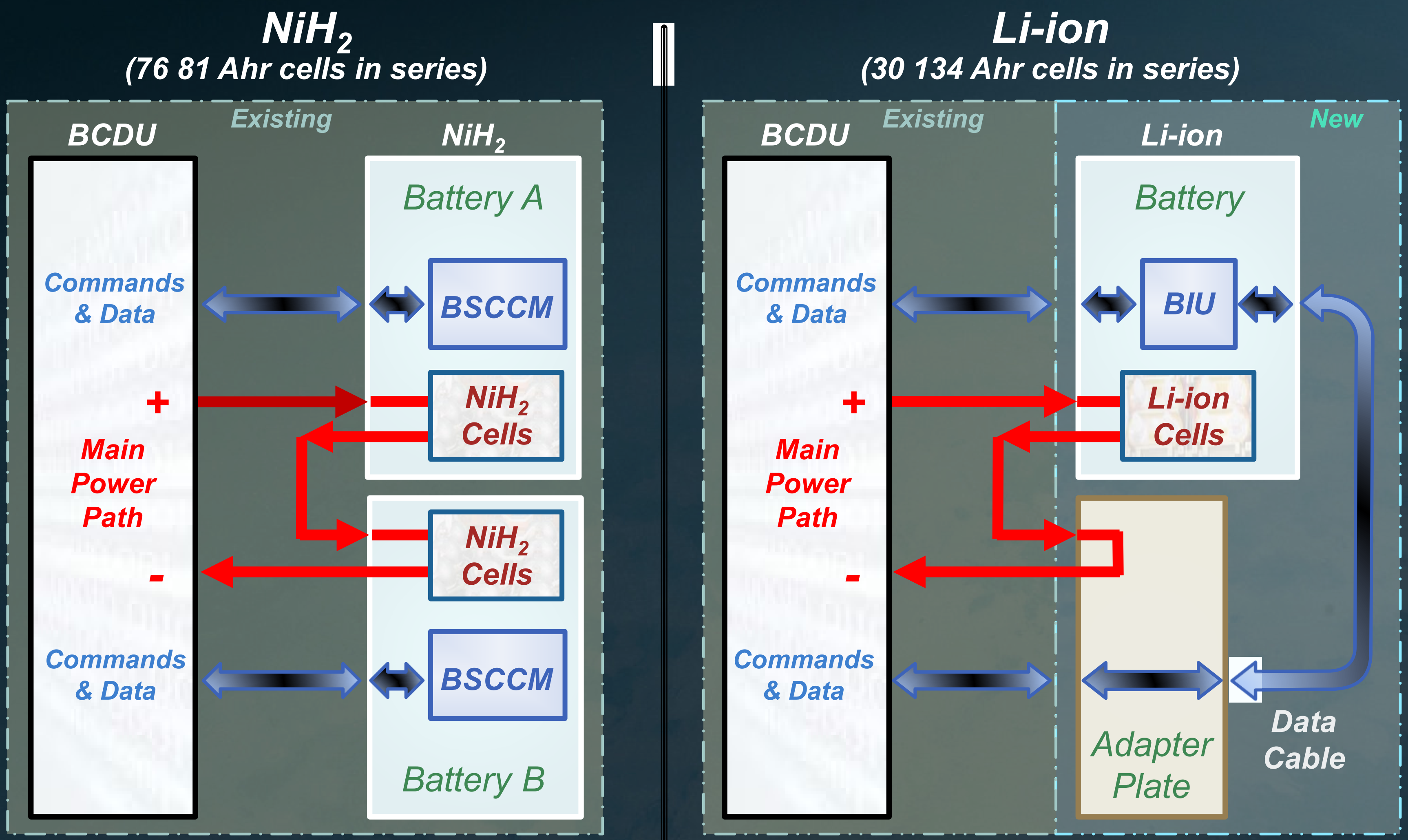
Initial Configuration:

- 6 NiH_2 ORUs (Orbital Replacement Unit) per 8 channels – 48 total

Final Configuration:

- 3 Li-ion ORUs per 8 channels – 24 total

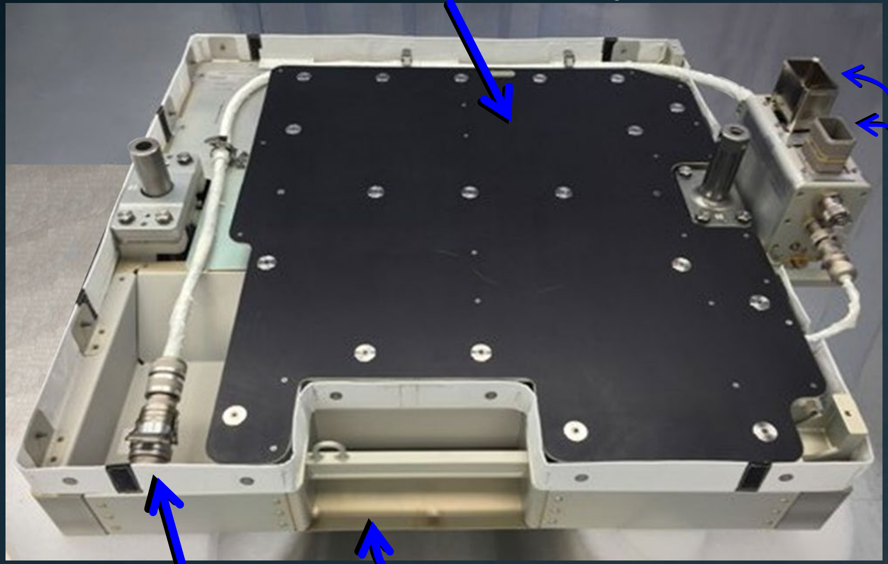
ISS Upgrade to Li-ion



BCDU: Battery Charge / Discharge Unit
BIU: Battery Interface Unit
BSCCM: Battery Signal Conditioning and Control Module

ISS Li-ion Orbital Replacement Units

Heater Mat
Heater Plate Assembly



P4 Connector
(stowed for launch)

EVA
Hand Hold &
Tether

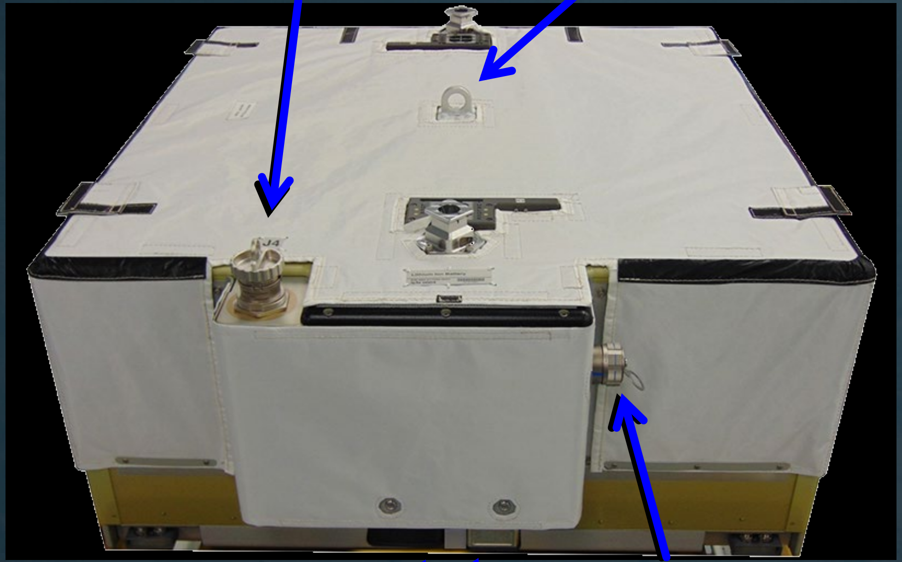
Dummy
Connectors

Adapter Plate ORU

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

J4
Connector

EVA
Tether



P1 & P2
Connectors

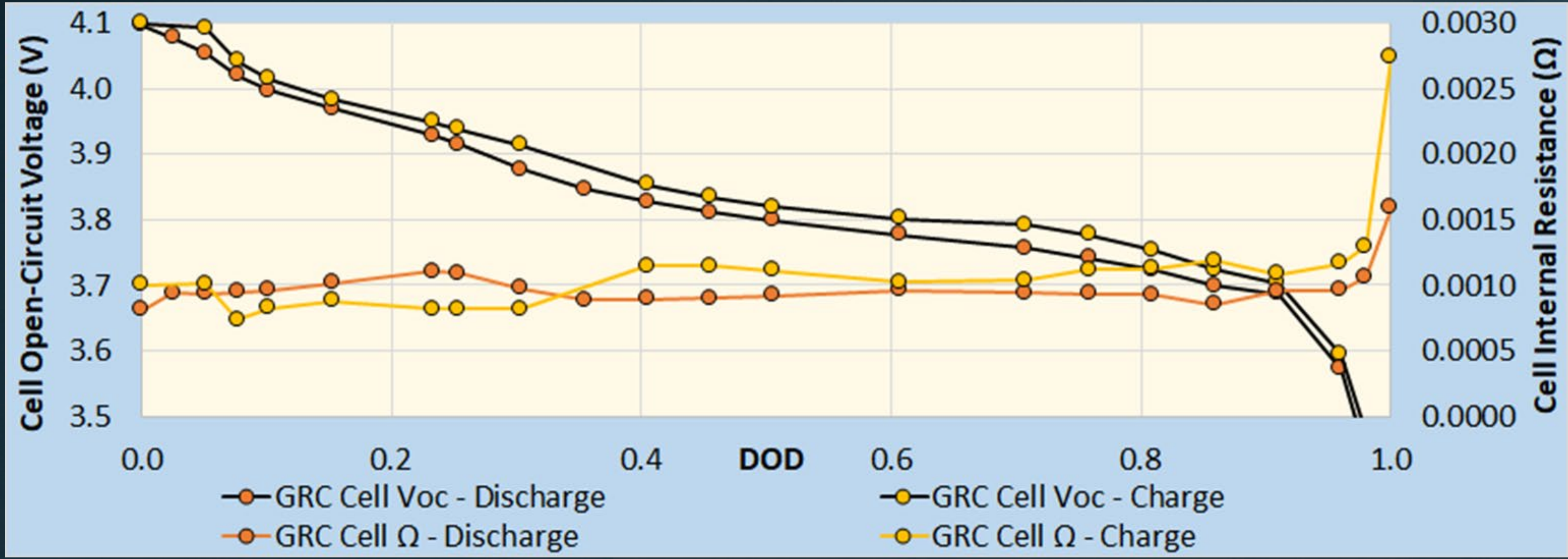
J3 Test
Connector

Li-ion Battery ORU

Dimensions (LxWxH): ~ 41” x 37” x 21”
Spec Weight: 435 Lbs

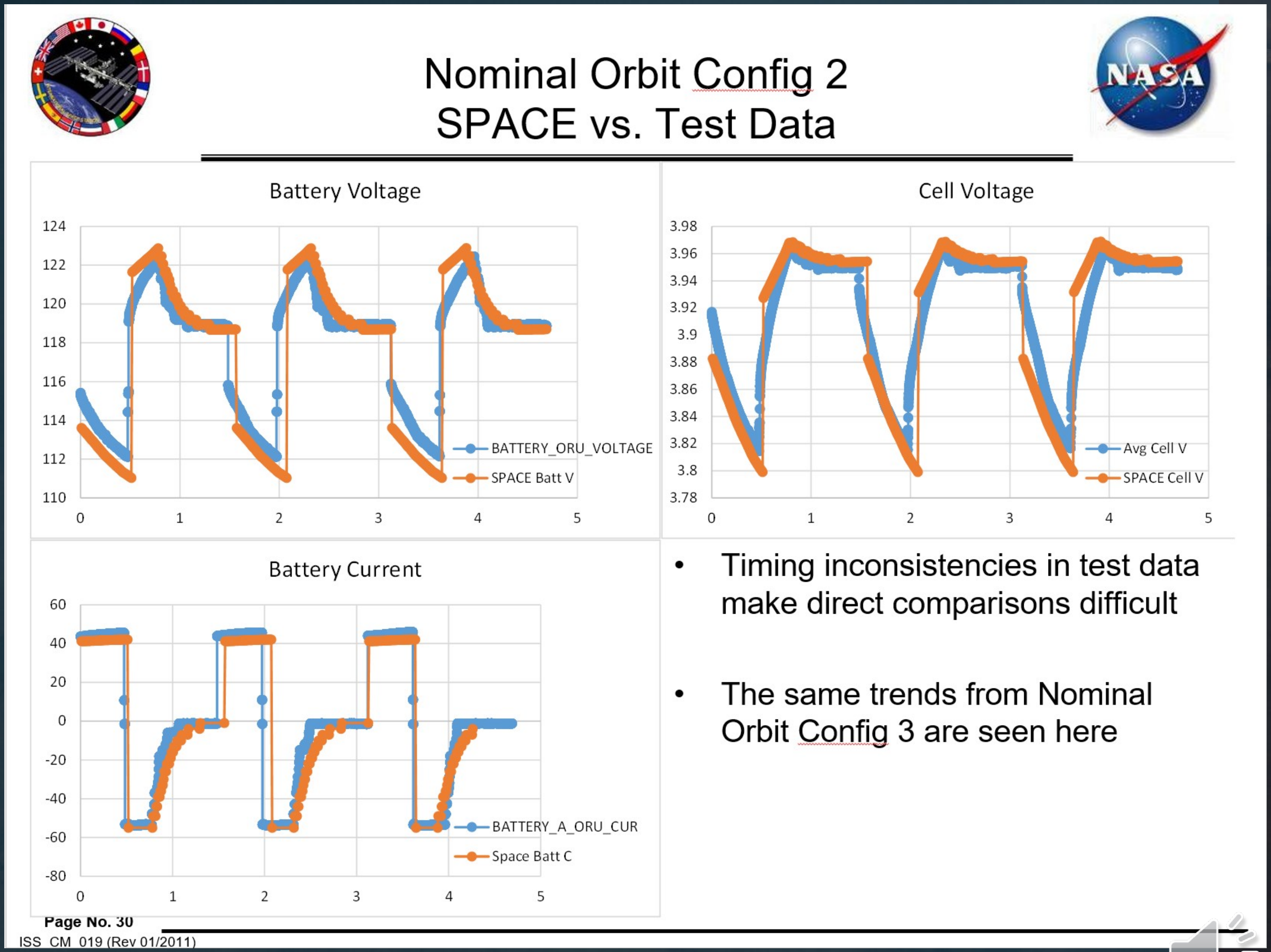
Building Li-ion Battery Model

- Analytical Li-ion battery model not part of deliverable from vendor
  - Developed a Li-ion computational model based upon cell characterization test data reference curves

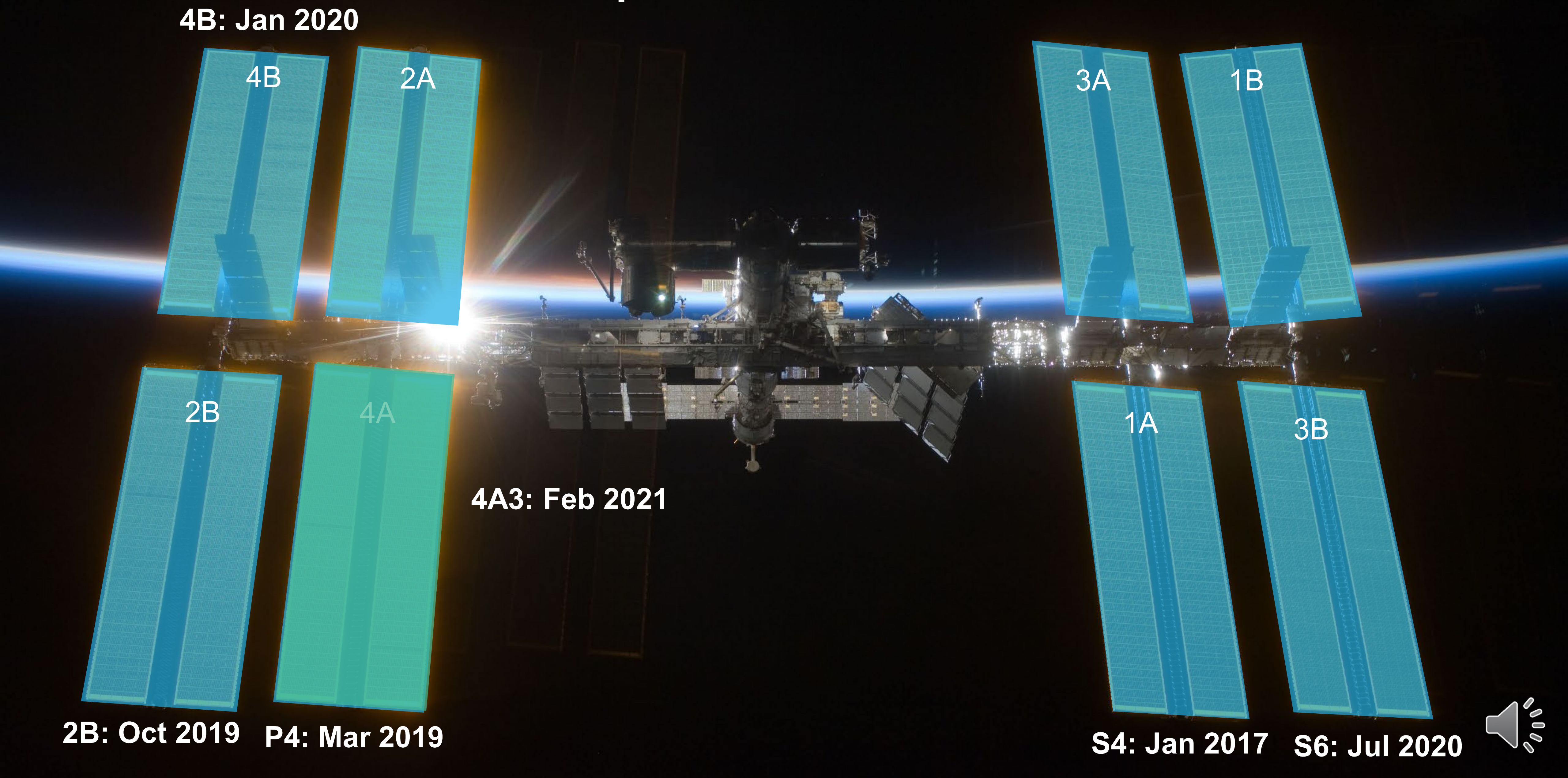


Li-ion Battery Model Challenges

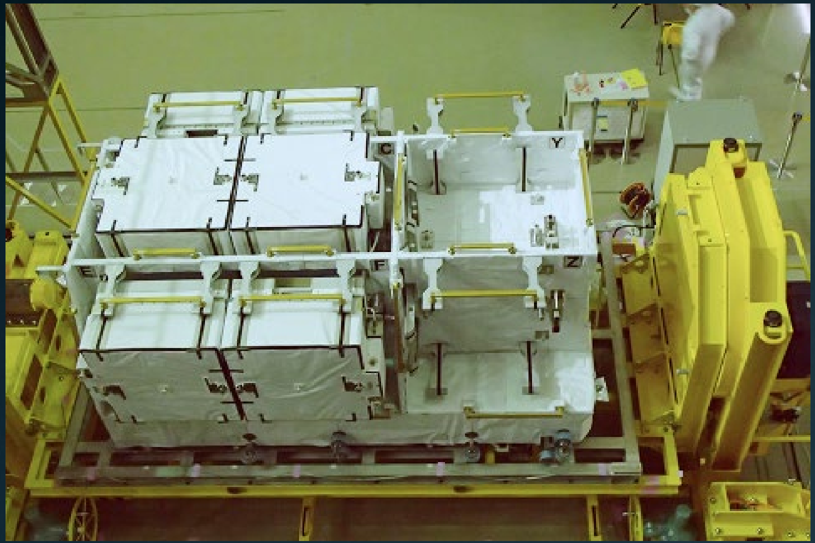
- Evaluated Li-ion battery model to orbit rate cycle testing of hardware
  - Consecutive “orbits” of hardware testing did not have consistent timing
  - Adjusted model inputs to get better matching of test data trends
  - Full model validation would occur after installation on-orbit
- Need to model some channels on NiH_2 batteries and some channels on Li-ion batteries



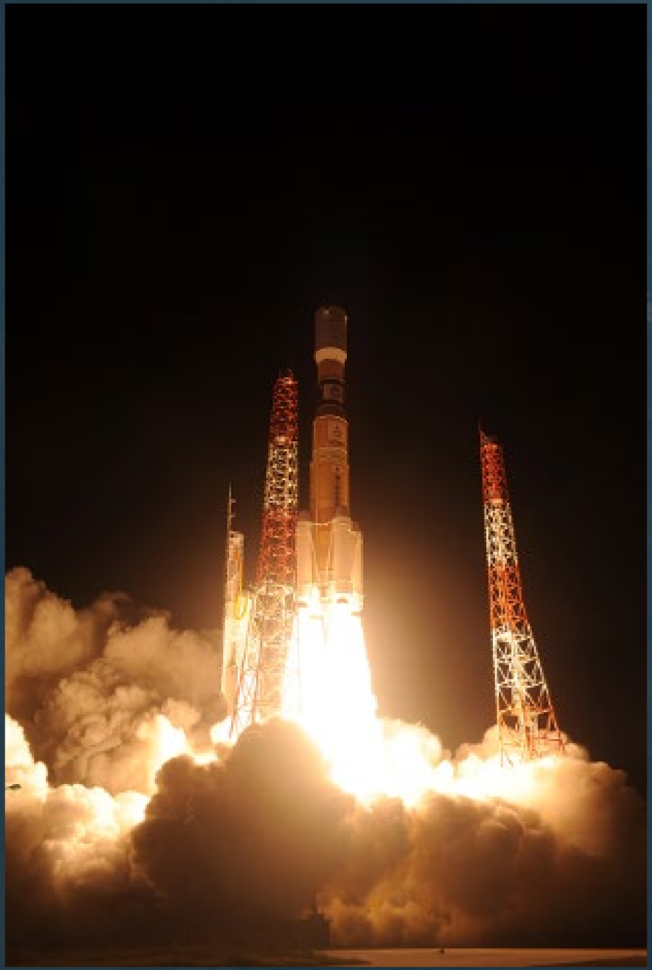
Li-ion Replacement Timeline



Battery Replacement: Ground Preparations

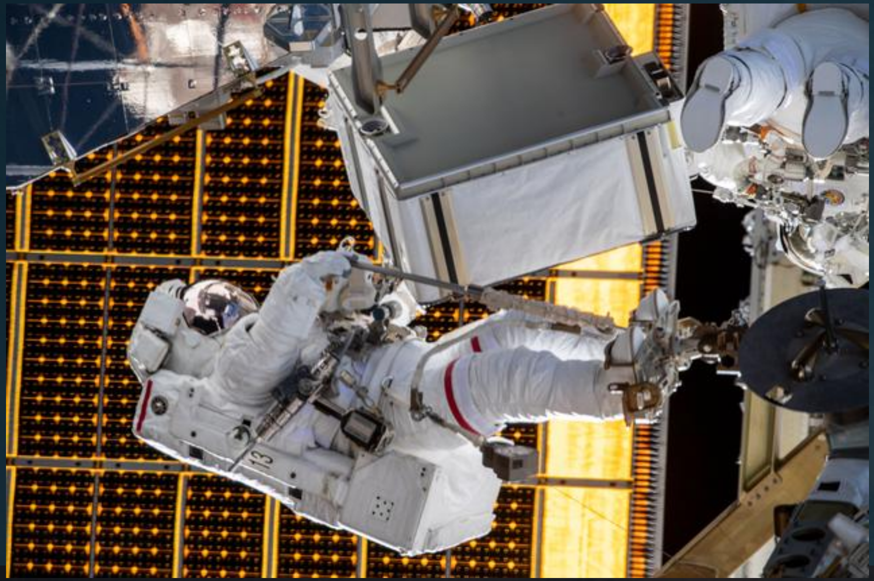


- Ship batteries and adapter plates to Tanegashima Space Center, Japan
- Install on HTV External Pallet (EP)
- Fully charge batteries prior to launch



Battery Replacement: On-orbit Procedures

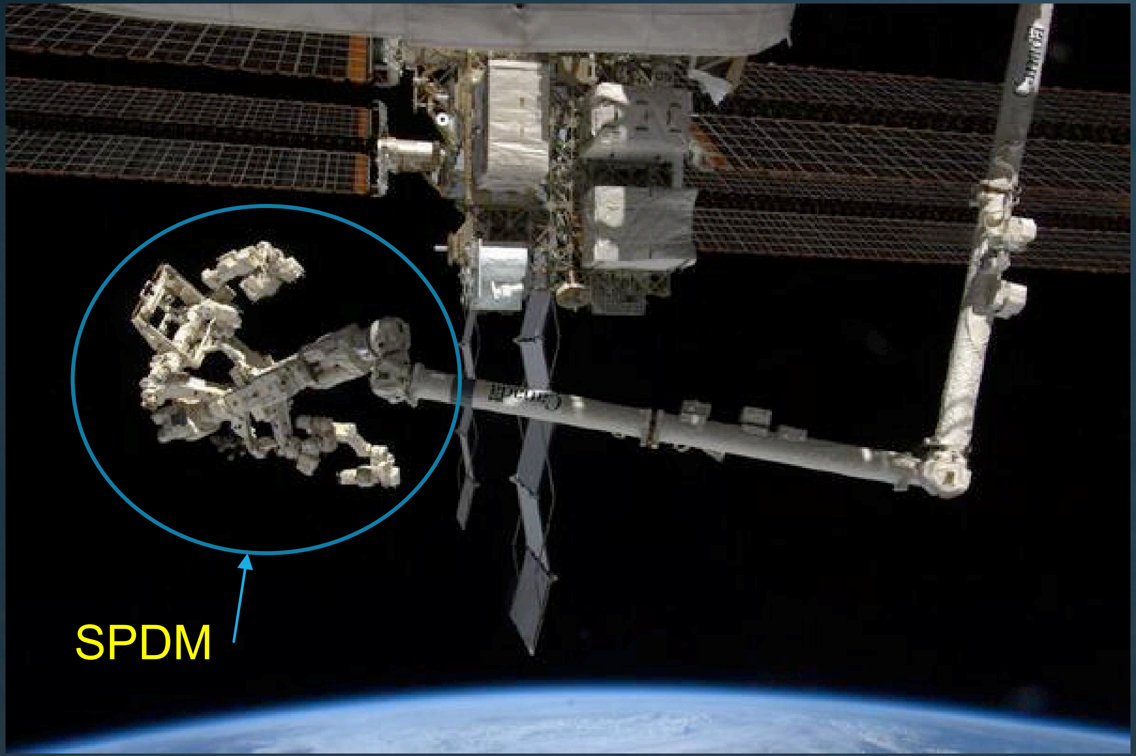
- Seamless Power Channel Handover (SPCH) of the channel
  - Draining the existing NiH_2 batteries
  - Reduce loads on supporting channel
- Robotic prep work
  - Extract external pallet from HTV, position near work site
  - Use Special Purpose Dexterous Manipulator (SPDM) to install batteries for inboard channels (P4, S4)
  - Robotic Arm / SPDM cannot reach outboard channels (P6, S6)



- EVA to finish
  - EVAs needed to connect adapter plate cable for all channels
  - Multiple EVAs needed for the complete installation of new Li-ions
- Thermal conditioning of batteries
- Power up and checkout of new hardware

S4: Leaking and EVA Crew Delays

- HTV6 cargo: Li-ion batteries for 1A and 3A
- Delay of HTV6 flight due to leaky pipes (scheduled 30 Sep 2016 - flew 9 Dec 2016)
  - Required expanding the solar betas analyzed
  - Risk of missing secondary launch opportunity. Would cause over an additional year of delay
  - Swapped out tanks between HTV6 and HTV7 due to leaks to make earlier launch
- Special Purpose Dexterous Manipulator (SPDM) grapple and release issues



- ISS Traffic
  - NASA EVAs require at least 3 NASA personnel on station.
  - Need to schedule EVAs around cases where there will limited vehicle traffic

P4: Flight Delays

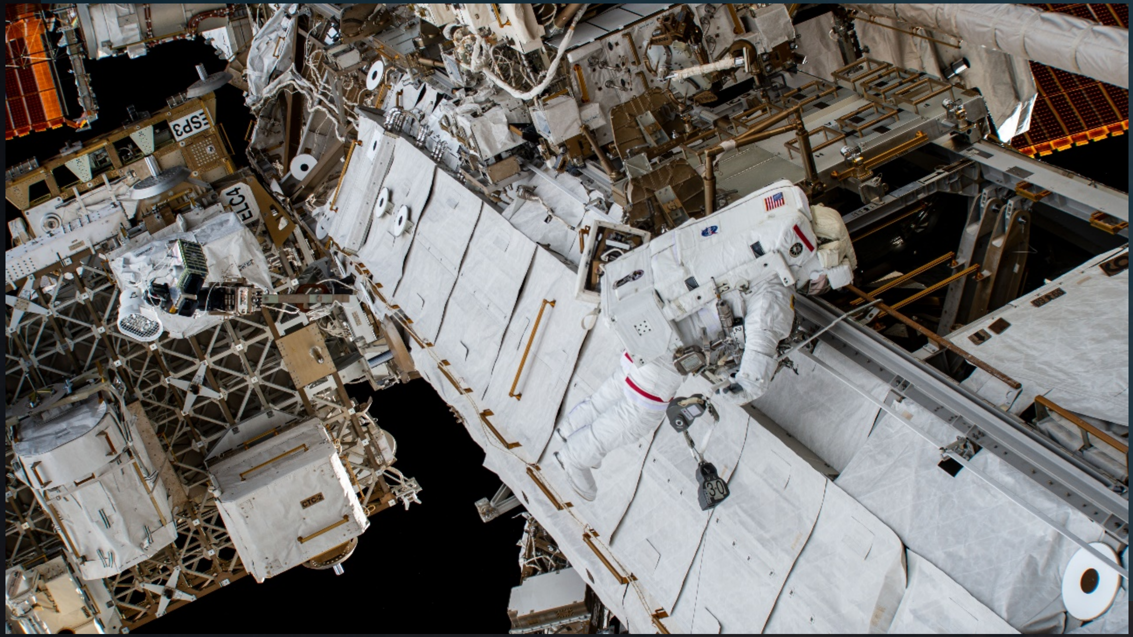
- HTV7 Flight Sept 2018
  - Channels receiving new Li-ion batteries were supported by some of the oldest set of solar arrays
  - Violated Flight Rule limits for extreme lighting case, solution proposed involved flying the station backwards (180° yaw maneuver)

- Soyuz MS-10 aborted launch Oct 2018
  - Delayed arrival of NASA crew to have enough crew for an EVA
  - HTV7 with Li-ion batteries were already on orbit, but HTV7 has limited life and needed to depart before installation could take place
  - Pallet removed from HTV and stored on ISS until battery installation
  - Thus installations were no longer tied to HTV being present
  - Cannot jettison a pallet, needs to be carried away by next HTV. Requires planning of pallet hand-offs

- Installation of the 2A and 4A Li-ion batteries occurred in March 2019 after sufficient NASA crew were available.

Spotlight: 4A3

- 4A3 BCDU tried to start up 4A3 Li-ion battery
  - Low temperature and low 1A current caused “stall” condition in the BCDU
  - “Stall” condition on degraded BCDU diode led to diode failure
  - Failed diode in BCDU Fault Isolator caused blown fuse in the new 4A3 Li-ion battery



- BCDU replaced with on-orbit spare
  - Replaced failed Li-ion battery with old NiH_2 battery
    - If left at 2 batteries, use reduced peak power limit
    - Therefore decision to reinstall NiH_2 battery
  - Resulted in mixed chemistry channel, 2 Li-ion batteries, 2 NiH_2 ORUs, from Sep 2018 to Feb 2021

2B: Multiple Crew EVAs

- HTV8 brings up next set of Li-ion batteries in Sep 2019
  - First installations on outboard channels (P6). Robotic appendages cannot reach these locations. All work must be performed by EVA crew
  - Planners unsure how many EVAs it will take to change out batteries
  - Considerations made to determine if a hybrid EVA would be necessary. Each channel would get two dedicated EVAs and half of another EVA (i.e. 5 total EVAs for two channels)
  - Transition for first channel, 2B, is completed in two EVAs

Spotlight: 2B2

- After 2B Li-ion battery installation, 2B2 BCDU failed to power up
  - Again, low temperature, low current start up caused BCDU “stall” condition
  - 2B2 Li-ion battery not impacted
- Replaced 2B2 BCDU with on-orbit spare
  - Success: 2B - 3 operational Li-ion batteries
  - 2B2 BCDU returned to the ground for investigation, recertified for flight

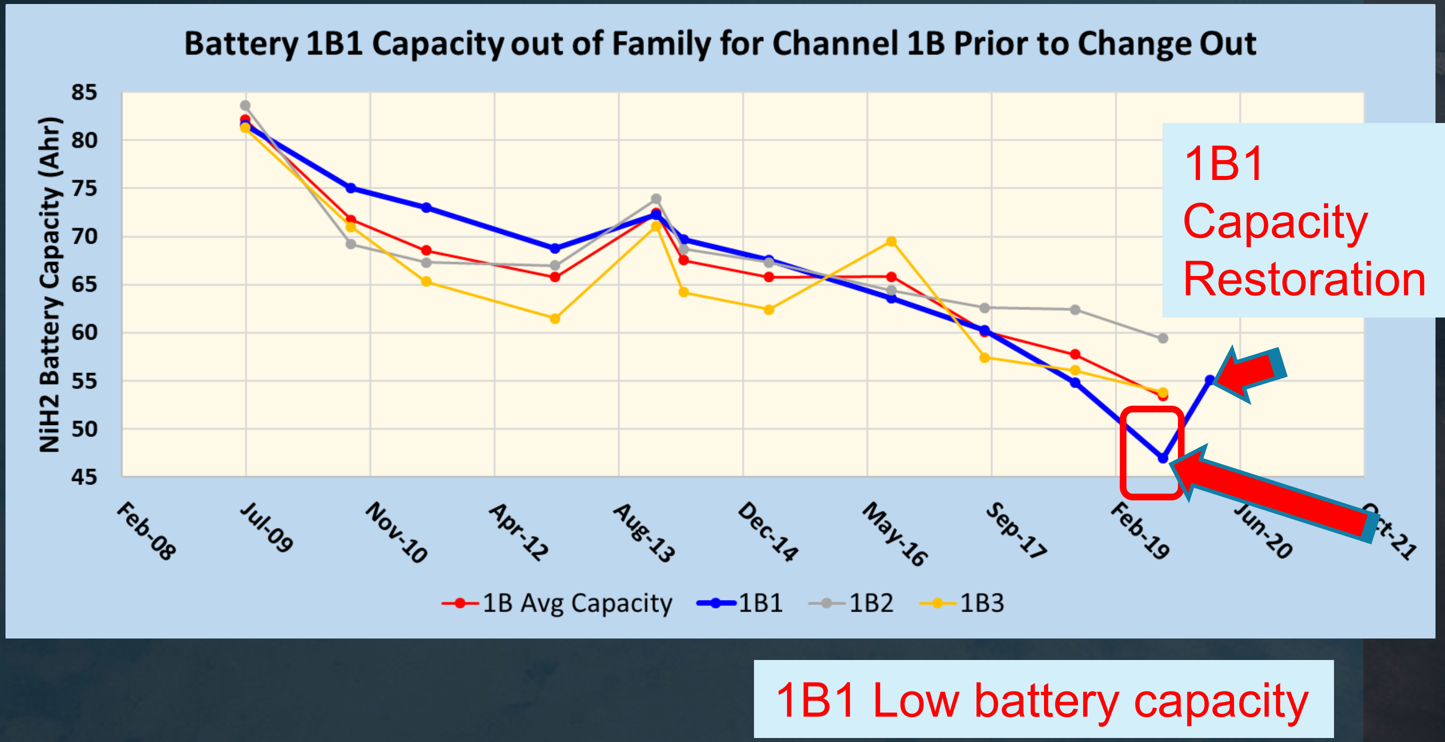
- Delay 4B Li-ion battery replacement to better understand BCDU issues
  - All battery capacity testing temporarily halted
  - 2 on-orbit BCDU spares left
- BCDUs are currently 10 – 20 years old.

4B: Modified Start Up

- Battery installations continue
  - Incorporated new start up procedure – 10 amp and -5°C on BCDUs (previous failures had been at 1 amp, -17 °C)
  - Second channel on P6 completes transition to Li-ion batteries in two EVAs
  - No failures occur. ISS teams breathe a big sigh of relief

Low 1B1 Capacity before Replacement

- GRC time phased power analysis showed insufficient margin due to NiH_2 battery 1B1 low capacity, prior to 1B Li-ion battery replacement
- Led to 1B1 conducting battery reconditioning
  - Difficult decision: 1B1 low battery capacity identified after 2B2 BCDU failure and recommendation to not conduct further NiH_2 battery capacity testing or battery reconditioning



S6, 4B Hiccup, and 4A3

- Li-ion batteries for 1B and 3B installed and powered up nominally
- 4B1 BCDU fault isolator for Li-ion tripped followed by 4B channel shut down
  - Oscillation on 4B bus caused excessive charging in BCDUs from additional partial shadowing on 4B at high solar betas
  - Would have happened during earlier high solar beta periods if Li-ion batteries had been installed
  - Update to BCDU firmware in process
- Successfully installed final Li-ion battery, 4A3, on 1 Feb 2021
- Break out the Celebratory Liquids

Lessons Learned

- Obtain vendor analytical battery model
  - Make battery model delivery part of the vendor contract
- Encourage useful ground test data
  - Find out when the ground tests are being conducted, encourage the test plan to simulate on-orbit use *(“Test as you fly; fly as you test”)*
- Prepare for project extensions and plan spares, spares, and more spares
- Adapt quickly
  - Events outside one’s control can muck up the works
  - Build flexible modeling code – may need to model unplanned configurations

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