

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

SPACE POWER WORKSHOP

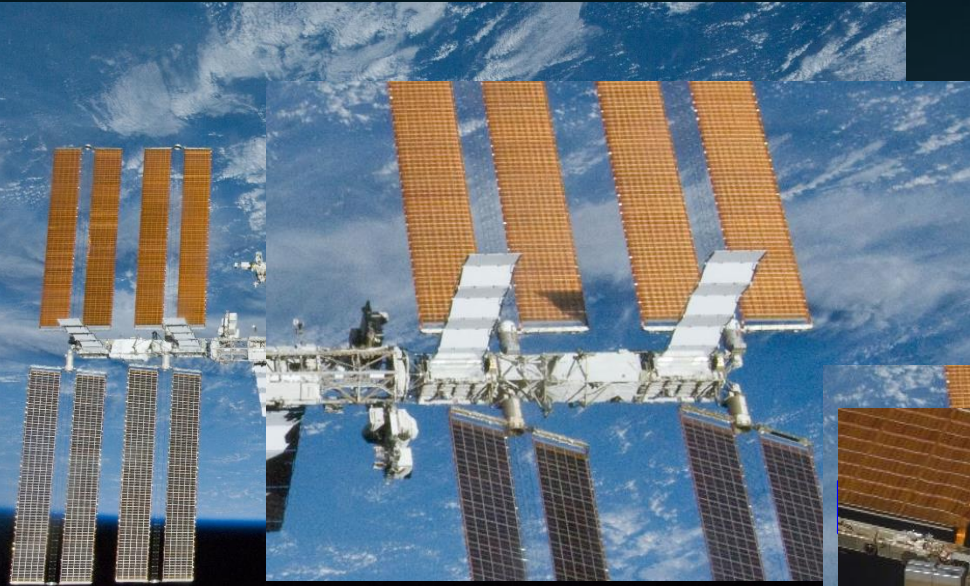
19 APRIL 2021

Ann Delleur
Steven Korn
Sarah Tipler
Penni Dalton

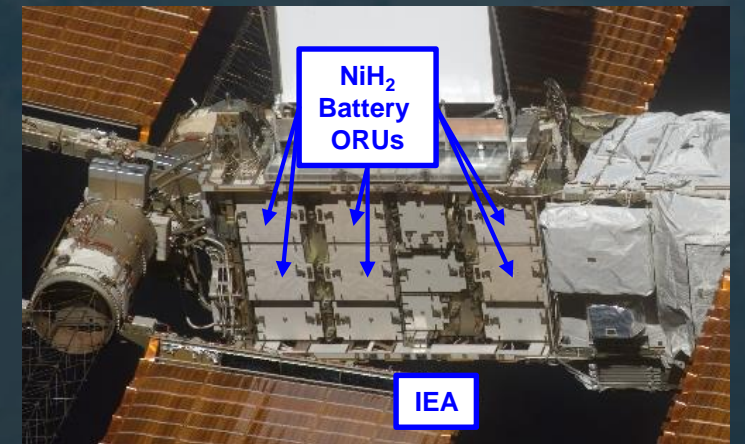
NASA Glenn Research Center
NASA Glenn Research Center
NASA Glenn Research Center
NASA Glenn Research Center

ISS Configuration - Battery Locations

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



8 Power Channels total



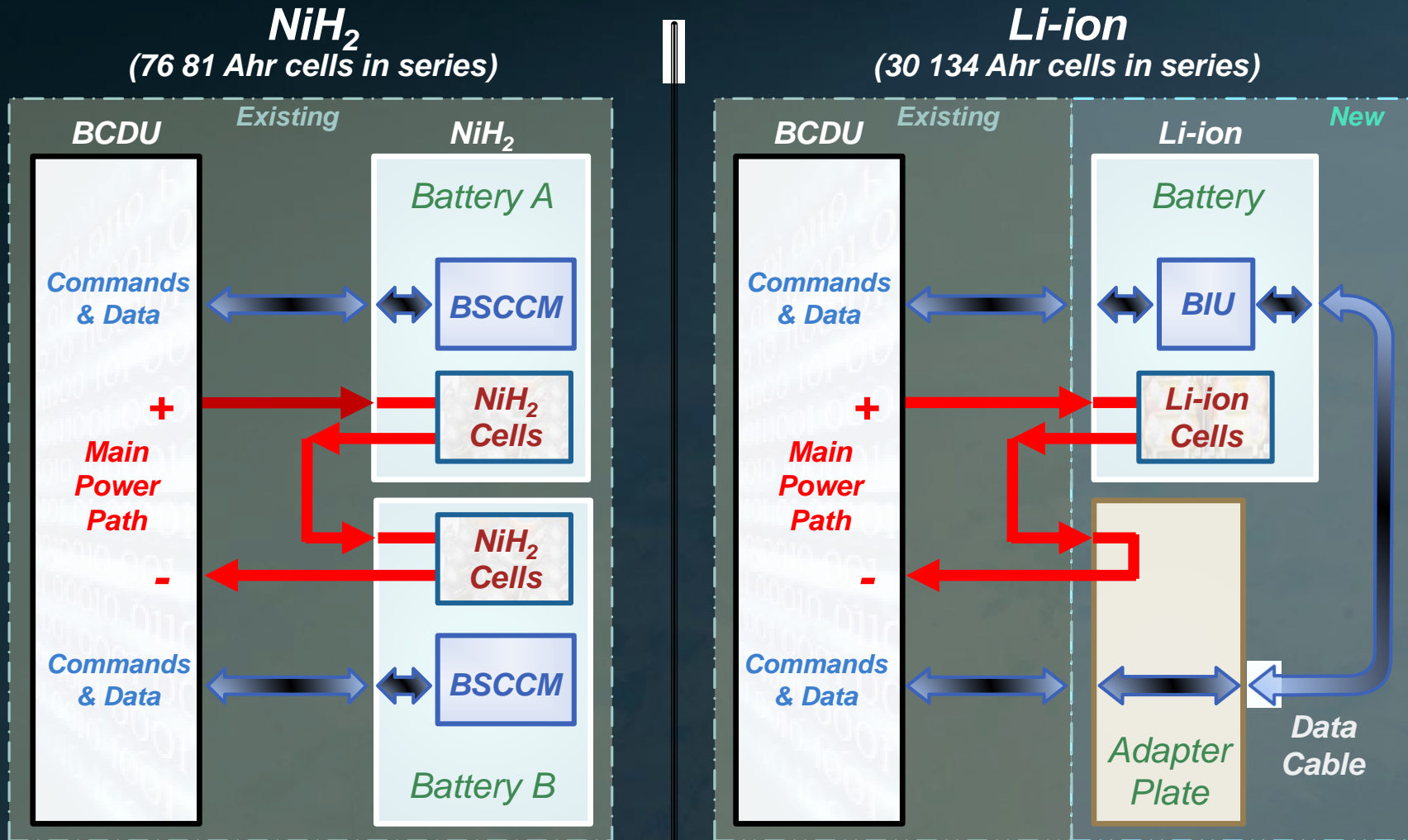
Initial Configuration:

- 6 NiH₂ ORUs per 8 channels – 48 total

Final Configuration:

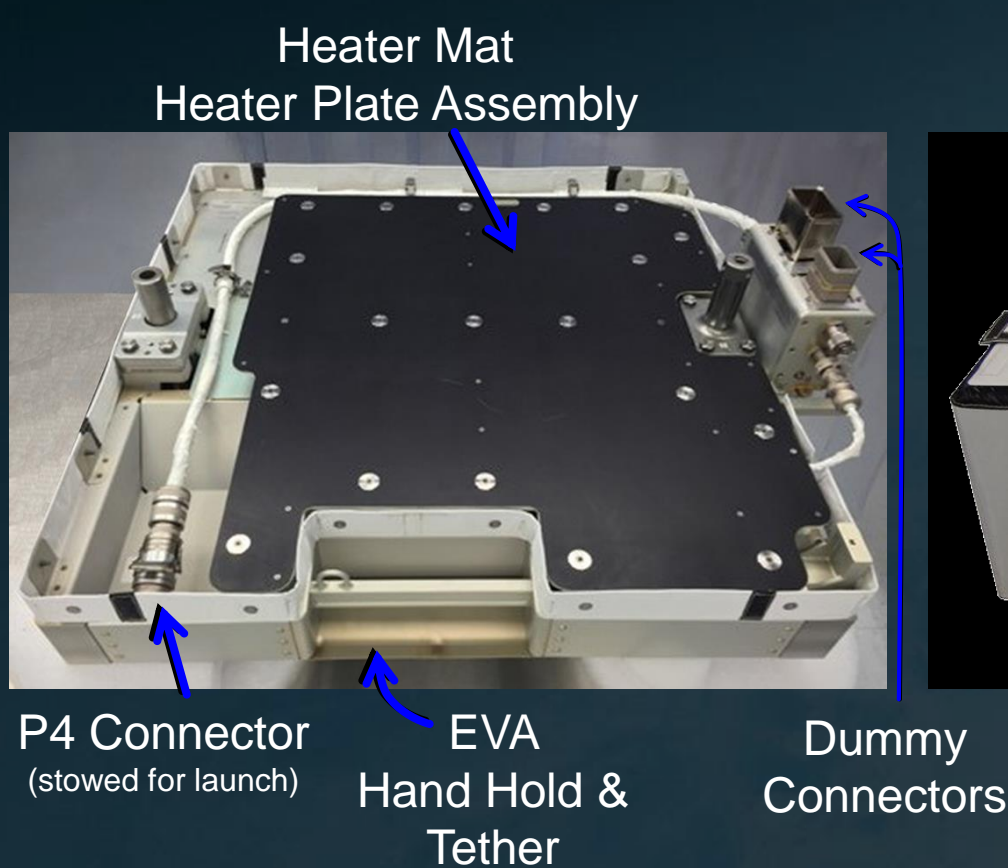
- 3 Li-ion ORUs per 8 channels – 24 total

ISS Upgrade to Li-ion



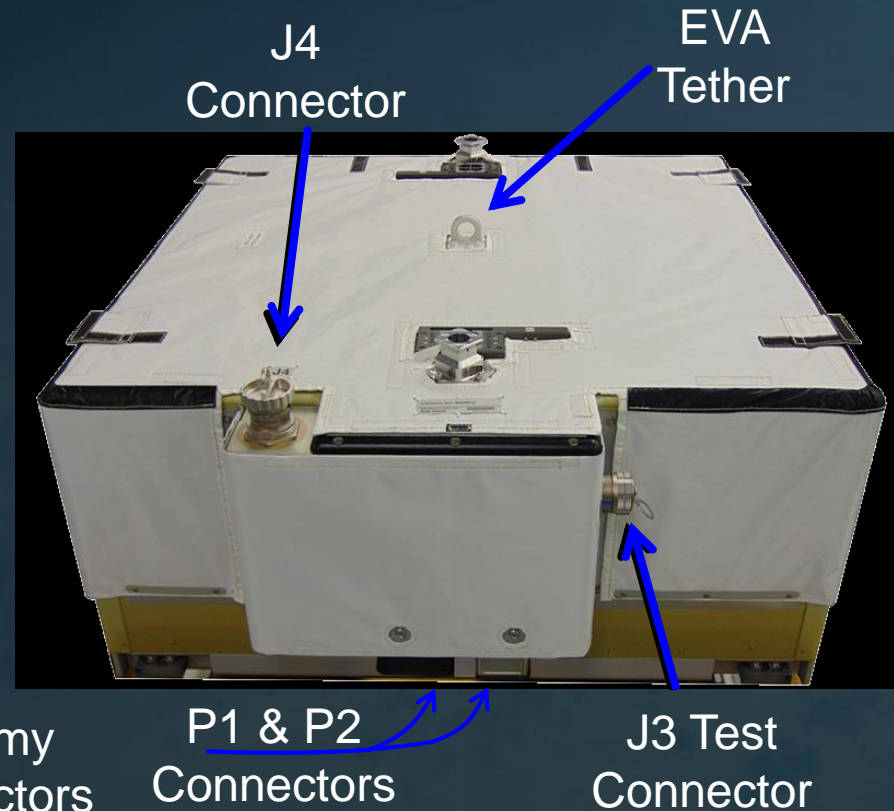
BCDU: Battery Charge / Discharge Unit
BIU: Battery Interface Unit
BSCCM: Battery Signal Conditioning and Control Module

ISS Li-ion Orbital Replacement Units



Adapter Plate ORU

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

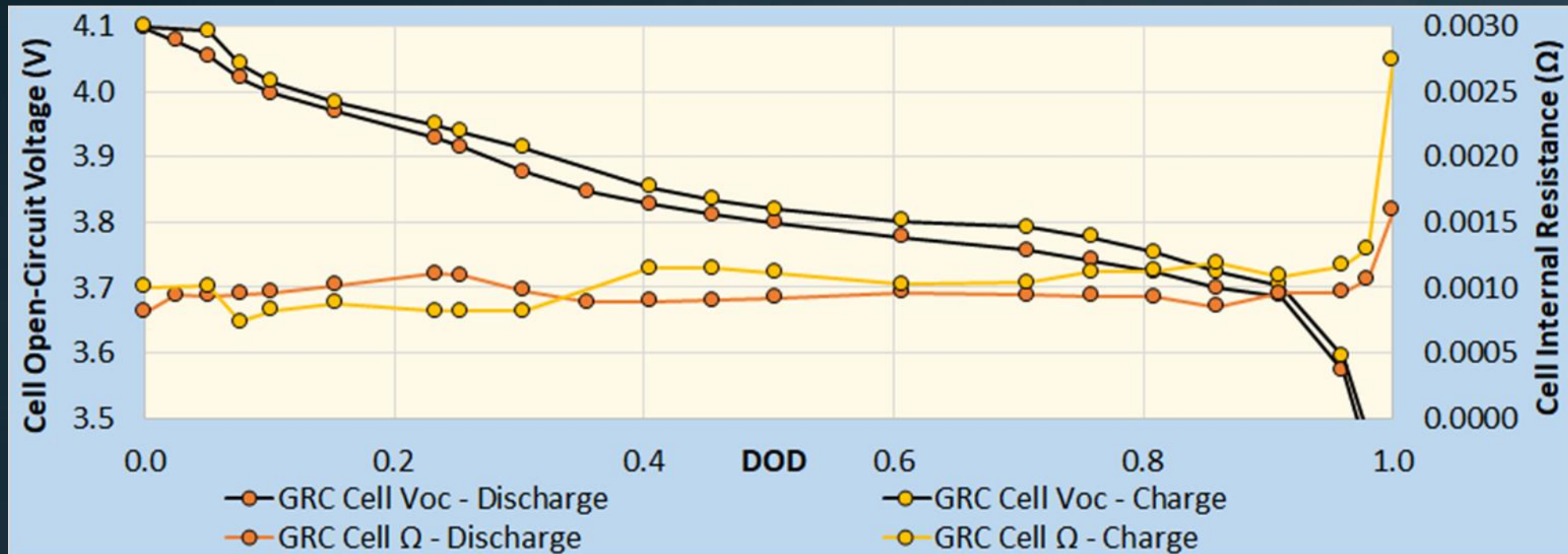


Li-ion Battery ORU

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

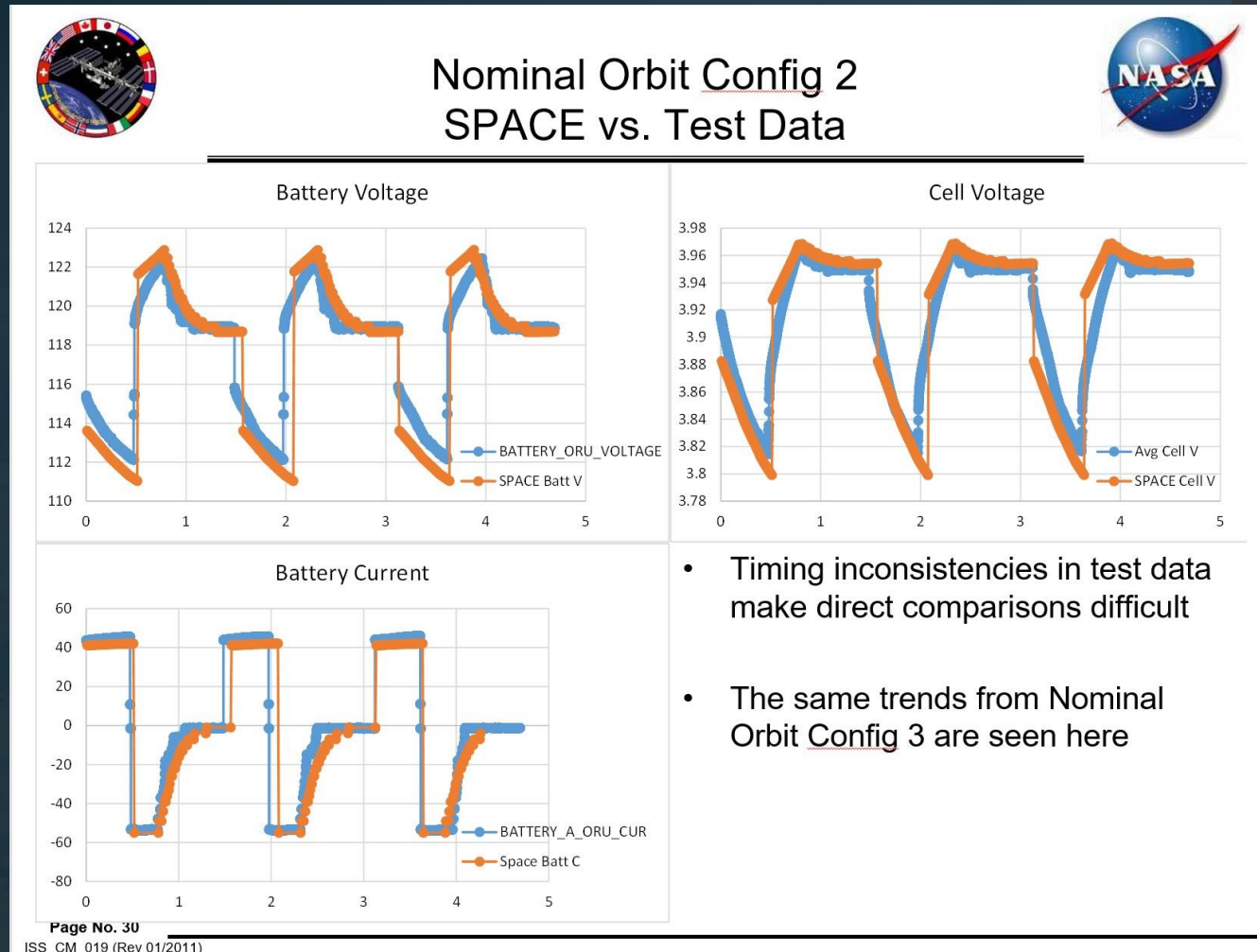
Building Li-ion Battery Model

- ▶ 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 NiH₂ batteries and some channels on Li-ion batteries



Li-ion Replacement Timeline

4B: Jan 2020

4B

2A

3A

1B

2B

4A

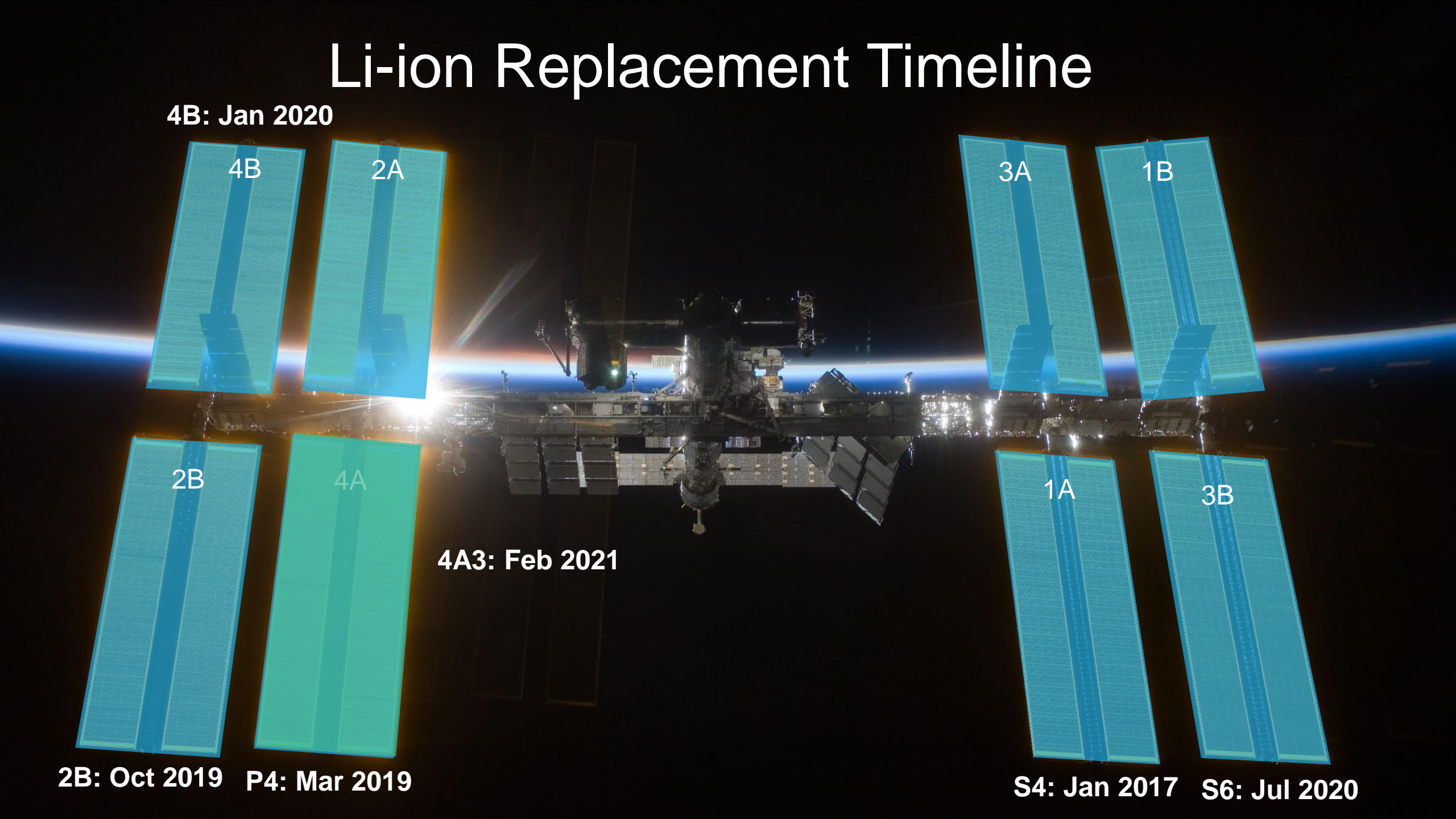
1A

3B

4A3: Feb 2021

2B: Oct 2019 P4: Mar 2019

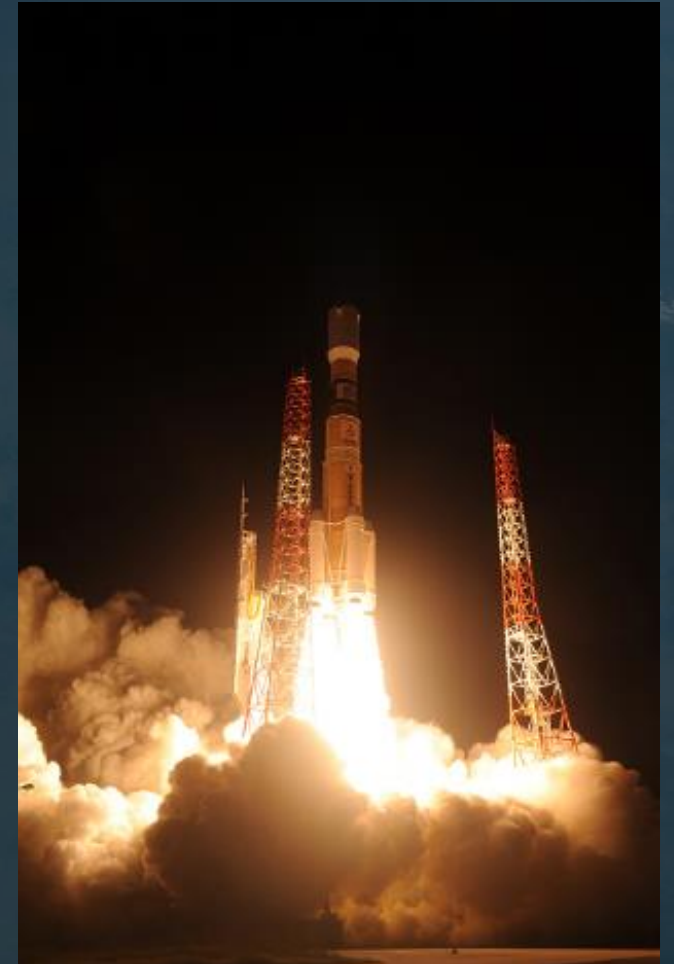
S4: Jan 2017 S6: Jul 2020



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

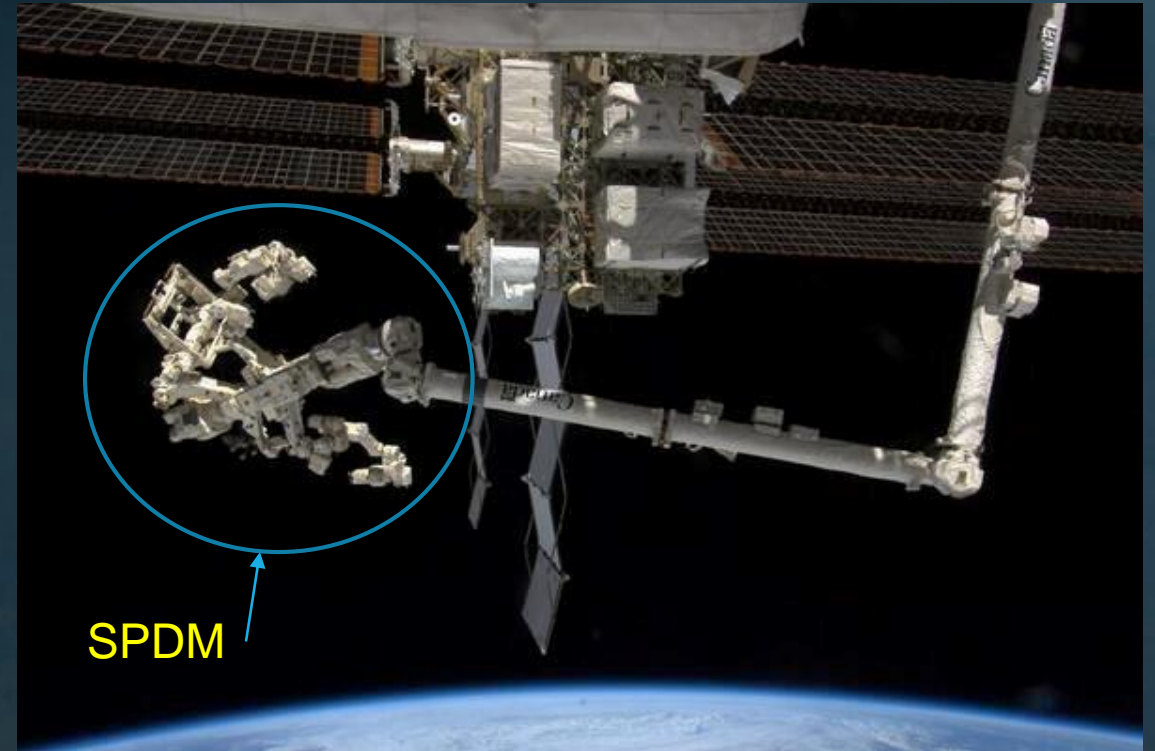
- ▶ Seamless Power Channel Handover (SPCH) of the channel
 - ▶ Draining the existing NiH₂ batteries
 - ▶ Reduce loads on supporting channel
- ▶ Robotic prep work
 - ▶ Extract external pallet from HTV, position near work site
 - ▶ Use Special Purpose Dexterous Manipulator (SPDM) to install batteries for 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



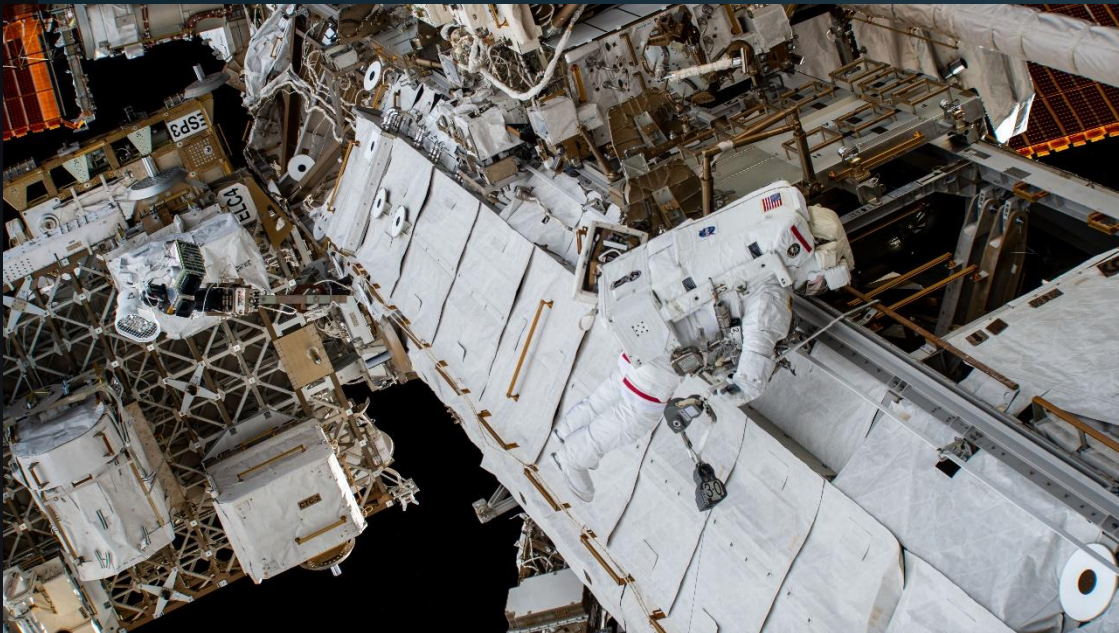
P4: Flight Delays

- ▶ HTV7 Flight Sept 2018
 - ▶ Channels receiving new Li-ion batteries were supported by 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 NiH₂ battery
 - ▶ If left at 2 batteries, use reduced peak power limit
 - ▶ Therefore decision to reinstall NiH₂ battery
 - ▶ Resulted in mixed chemistry channel, 2 Li-ion batteries, 2 NiH₂ 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.**



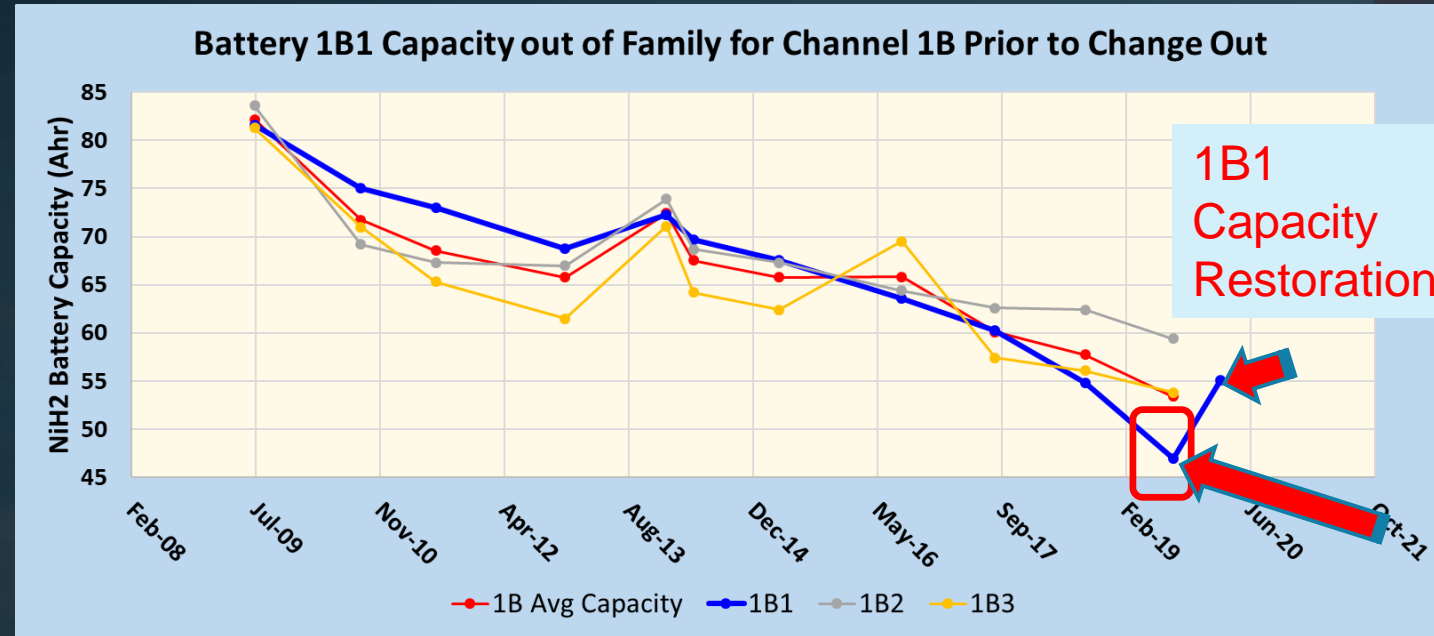
4B: Modified Start Up

- ▶ 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 NiH₂ 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 NiH₂ battery capacity testing or battery reconditioning



1B1 Low battery capacity

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



Acknowledgements

The authors would like to thank the many folks who have contributed to the efforts and analysis included in this presentation

- ▶ Caroline Austin/NASA GRC
- ▶ Ebony Bowens/Boeing
- ▶ Ben Chisholm/SGT Inc
- ▶ Rich Fair/Barrrios Technologies
- ▶ Bob Klimek/NASA GRC (ret.)
- ▶ Dave Mckissock/NASA GRC (ret.)
- ▶ Sara Miller/NASA GRC (ret.)
- ▶ Tim North/Boeing
- ▶ Mike Way/NASA JSC