Photovoltaic Thermal Control System Flow Control Valve Duty Cycle After Addition of Lithium-Ion Batteries

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Introduction

- Lithium-Ion (LI) batteries were developed to replace the original batteries powering the International Space Station (ISS)

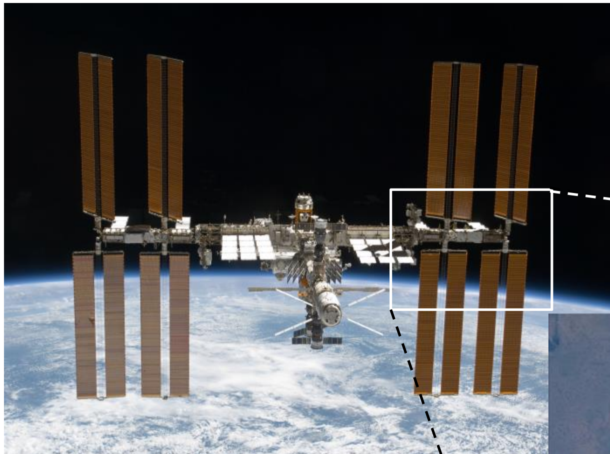
- Major thermal change
  - Battery packs based on LI instead of nickel-hydrogen (Ni-H2) cell
  - Active thermal system was optimized for Ni-H2
  - New batteries have different temperature limits from baseline
    - Ni-H2: 0 to 10 C
    - LI: 15 to 25 C

- The Photovoltaic Thermal Control System (PVTCS) maintains the ISS batteries and associated equipment within thermal limits, and maintains its own components

- The Active Thermal Control Systems (ATCS) team was tasked to integrate the new batteries into the existing PVTCS to achieve the new battery temperatures while also meeting the other requirements

Battery Locations on ISS

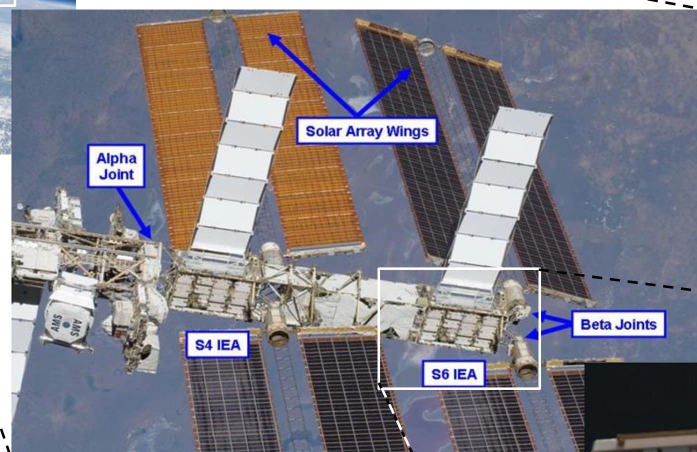
Batteries are located in the Integrated Equipment Assemblies (IEAs)

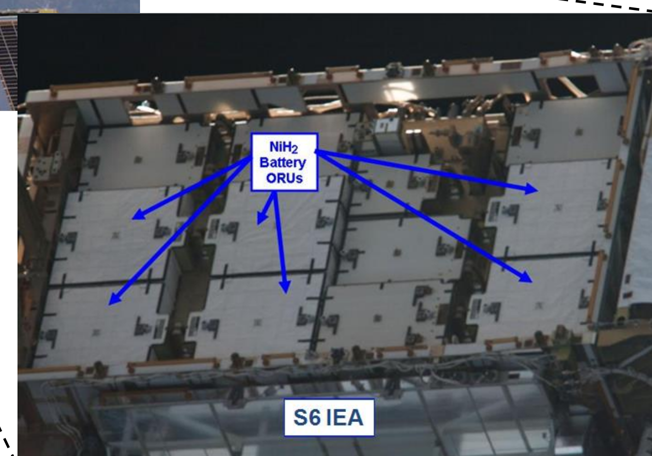


ISS has 4 IEAs

2 power channels per IEA - total of 8 channels on ISS

Each channel has a dedicated PVTCS





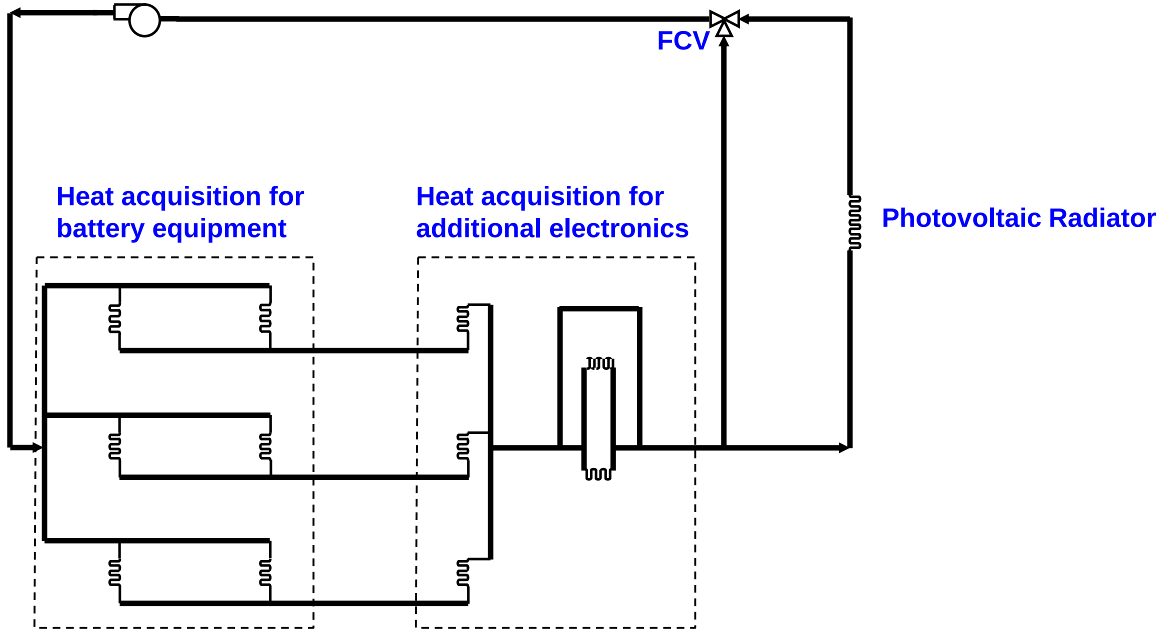
Ni-H2 Batteries
- 6 Ni-H2 Orbital Replaceable Units (ORUs) per channel
- 48 total Ni-H2 batteries

LI Batteries
- 1 LI ORU & 1 Adapter Plate (AP) replace 2 Ni-H2
- 24 total LI batteries

Photovoltaic Thermal Control System

- Anhydrous ammonia working fluid
- Constant speed pump
- Roughly constant ammonia flow rate

- Flow Control Valve (FCV) divides flow between radiator and bypass
- Controlled by software algorithm
- Valve spool rotates via actuator & geartrain
- $\theta \sim 0^o$: all bypass, $\theta \sim 90^o$: all radiator
- Slew rate of 9 ^{o}/sec

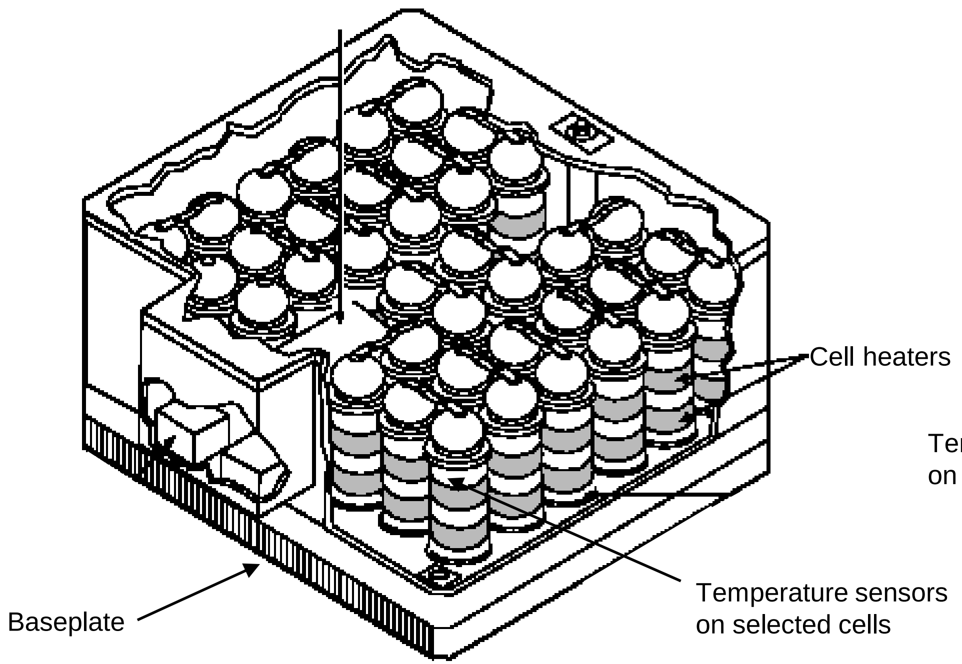


- System flow distributed among heat acquisition coldplates
- Cooling provided to battery equipment and additional electronics on the IEA

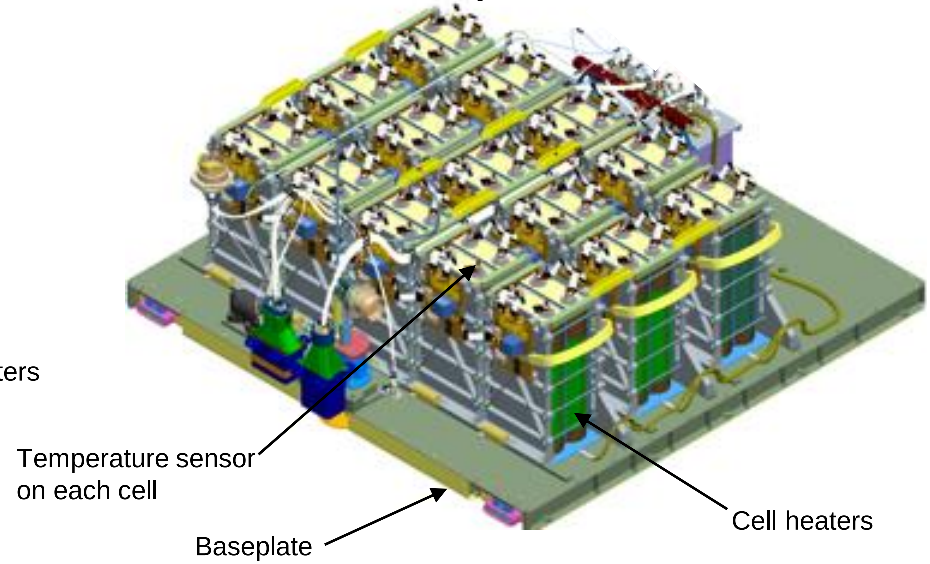
- Photovoltaic Radiator (PVR) situated downstream of the cooled equipment
- Provides heat transfer path from fluid to space heat sink

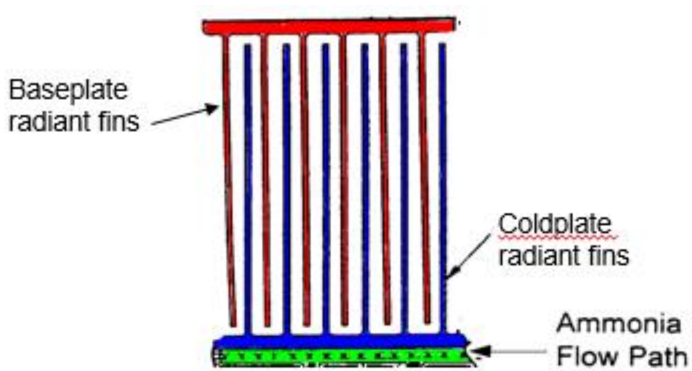
Ni-H2 and LI Batteries and Heat Transfer Path

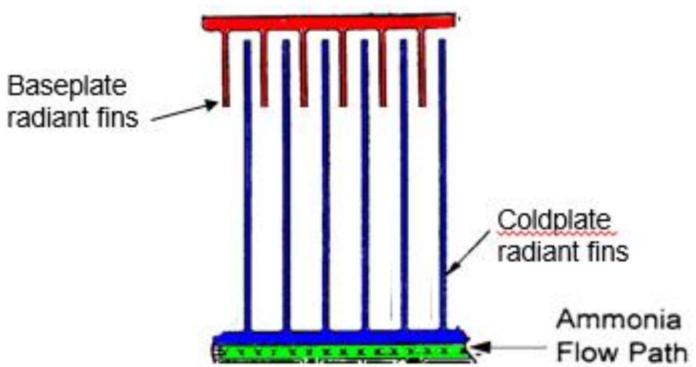
Original Ni-H2 battery ORU



New LI battery ORU



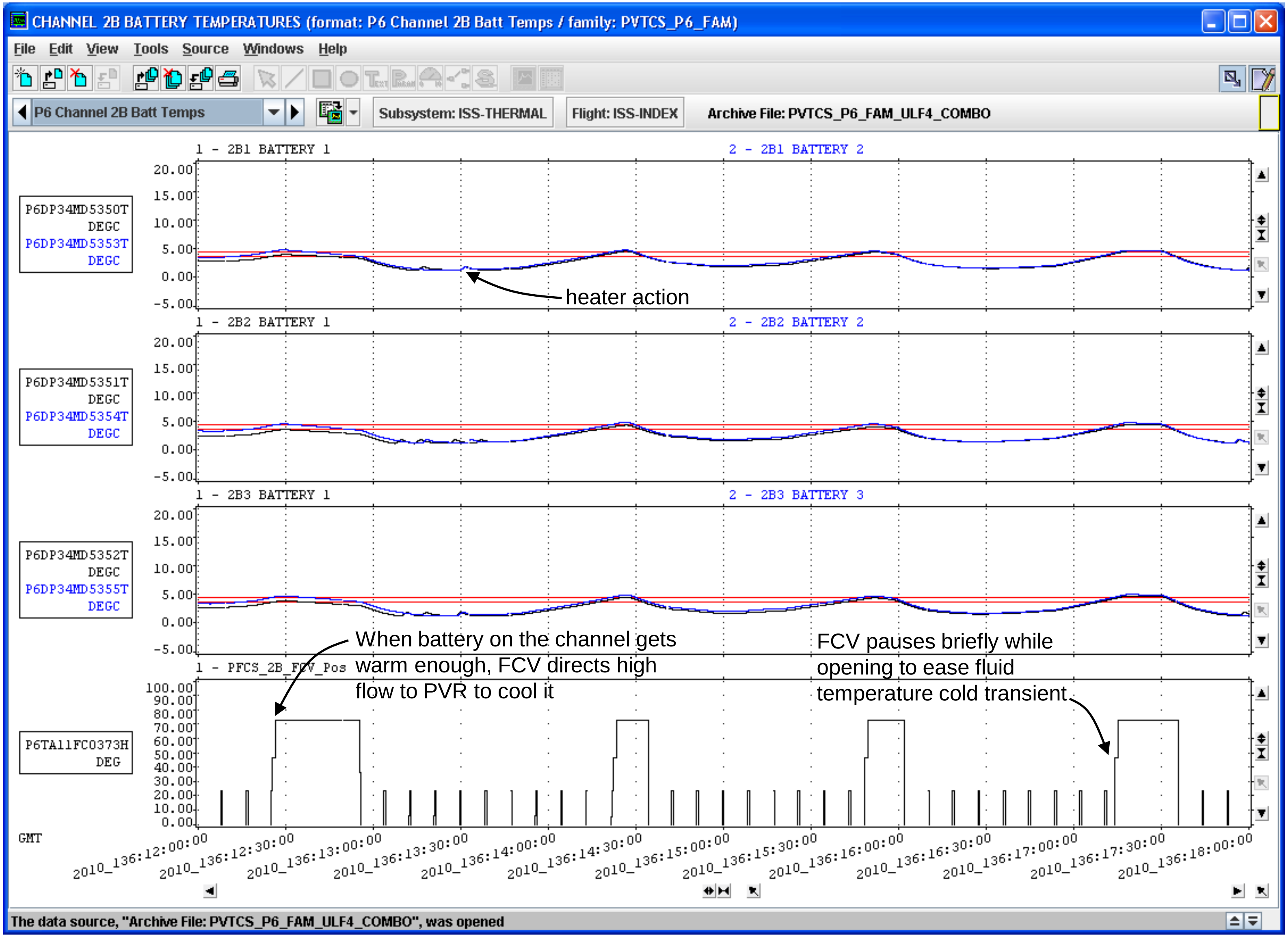




PVTCS Thermal Conditioning Algorithms

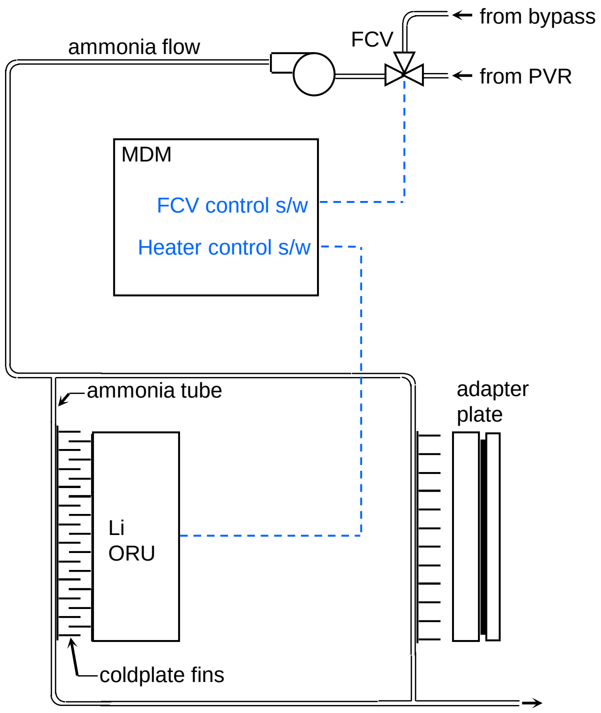
- PVTCS provides closed loop control of battery temperatures
- Utilizes FCV and heaters controlled by independent software algorithms
- System has an overall “compensation range” for cell temperature
  - Lower: temperature for cell heater activation
  - Upper: temperature for FCV to direct high flow through radiator
  - When cell temperature moves outside of the range, the system responds to drive the temperatures back into the range
- Heaters controlled on per ORU basis, FCV controlled on per channel basis

Typical Baseline Ni-H2 PVTCS Performance

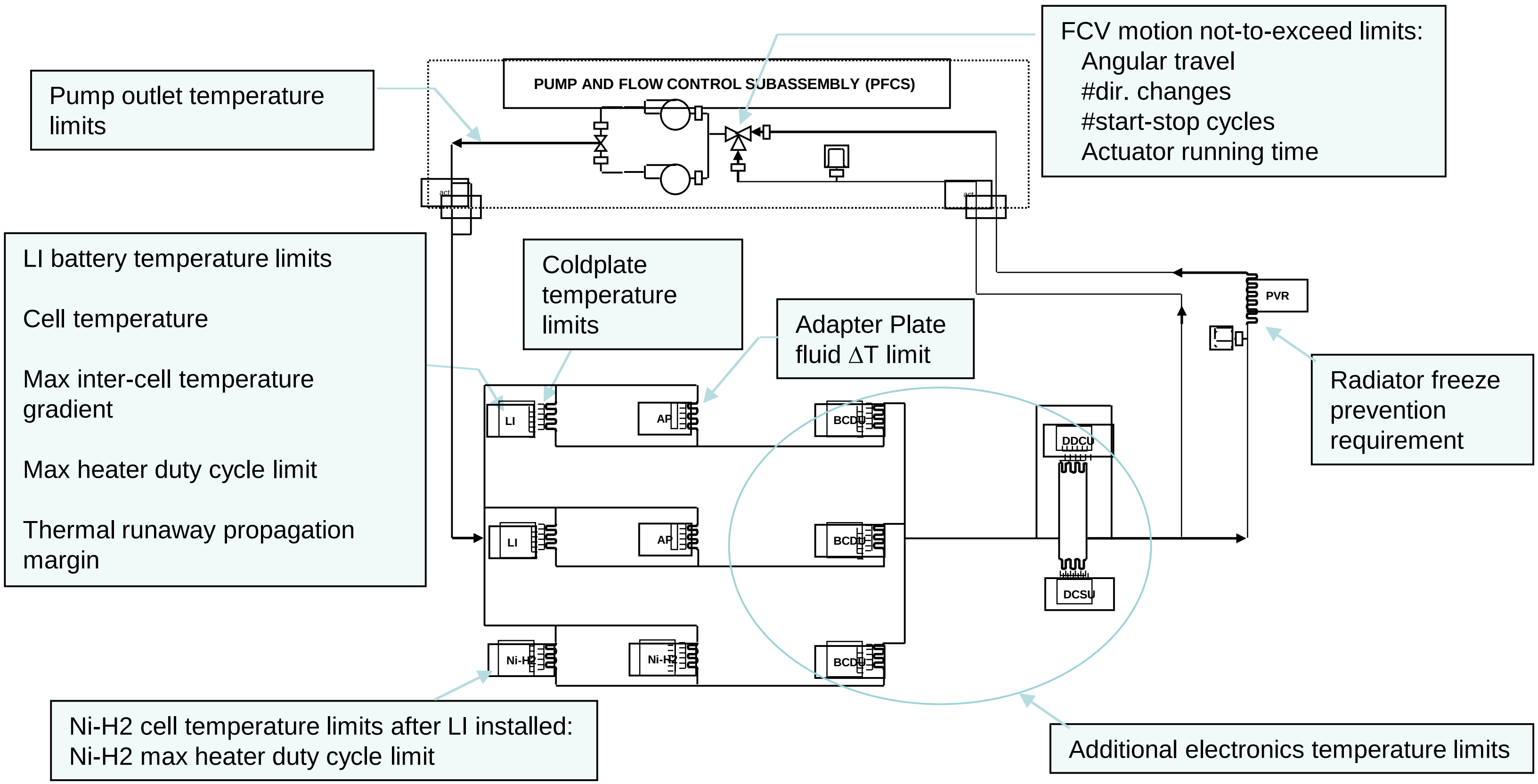


Integrating LI into the PVTCS Designed for Ni-H2

- Integration needed to result in:
  - Batteries within limits
  - PVTCS within limits
- Changeable:
  - LI ORU characteristics and heat transfer interface
  - Thermal control algorithms within the MDM
- Not changeable:
  - Fixed configuration of fluid lines, coldplates, radiator, PFCS, and FCV



Integration Challenge for PVTCS

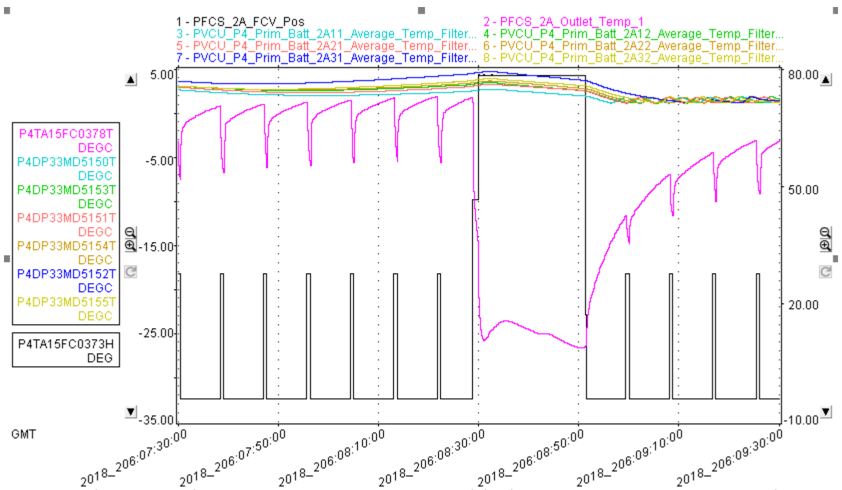


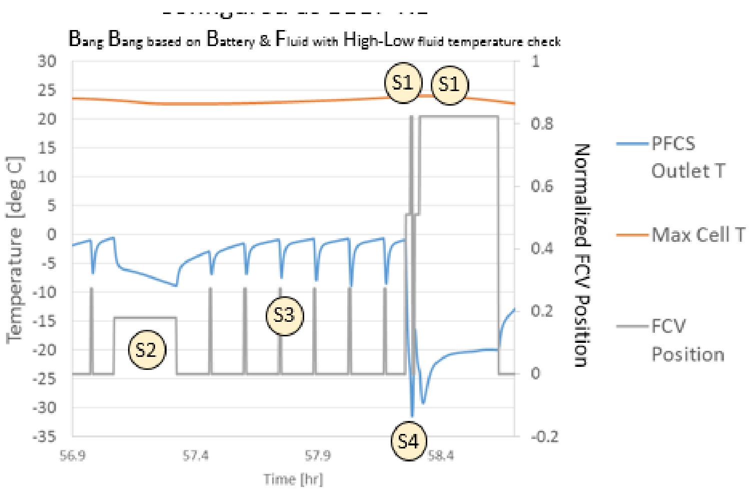
- PVTCS must thermally condition: batteries, associated equipment, and PVTCS equipment
- Needed solutions for both a full compliment of LI, plus a potential mixed configuration of LI and Ni-H2
- The approach was a broad integrated analysis using numerous configurations and conditions
- Assuring FCV motion to be within requirements was a subset of the larger body of work

FCV Algorithm Updates

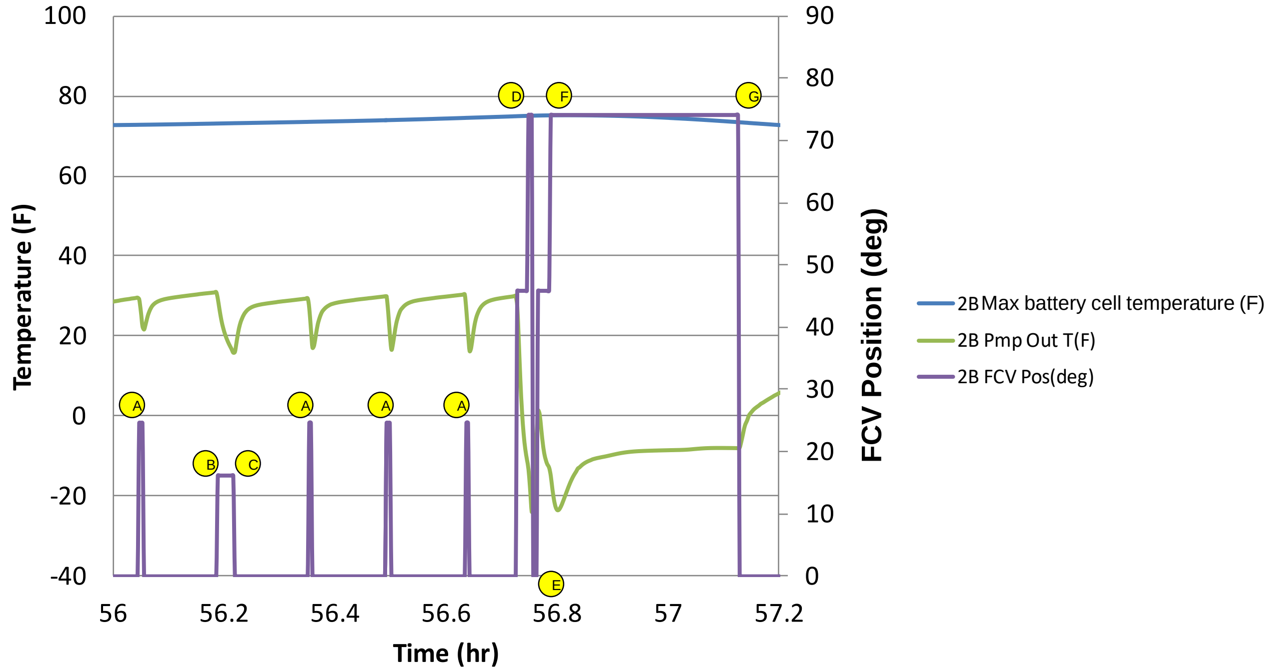
- Ni-H2
  - FCV responds to representative channel cell temperature
  - PVR is periodically flushed to prevent freeze

- LI
  - FCV responds to representative channel cell temperature
  - PVR is periodically flushed to prevent freeze
  - FCV responds to fluid temperature





FCV Algorithm Responses



A. Periodic PVR freeze protection

B. FCV responds to cool the PFCS outlet temperature after it has risen to 31 F

C. FCV returns to bypass after the PFCS outlet temperature has recovered to 16 F

D. FCV commanded to cool the LI batteries after the warmest of cells on a channel has risen to the action threshold of 75 F

E. FCV temporarily suspends cooling to the batteries to prevent over-cooling of the LI coldplates

F. FCV returns to battery cooling when the PFCS outlet temperature has recovered and risen to 0 F

G. FCV commanded to the bypass position when all of the LI cells on a channel are below the action threshold of 73.5 F

Integrated Analysis Overview

- Integrated PVTCS thermal-hydraulic model
  - External fluxes, radiation conductors, and sink temperatures
  - Input heat loads
  - Coldplate radiation, conduction, convection
  - Predicts temperatures throughout system, and FCV control response in the time domain

- Analysis parameters
  - Specification range of LI heat loading conditions
  - Spec heat loads for other components
  - Hot case and cold case on-orbit conditions
  - β range and flight attitudes
  - At Verification, ~960 transient analysis cases, each comparing all governed parameters to specification limits

FCV Motion Requirements

- PVTCS FCV position is monitored to detect excessive or unexpected motion
- FCV motion limits
  - Spec gives not-to-exceed limits on motion over 15 year lifetime
  - Consumption assessed annually

Parameter	Annual Limit
Degrees Traveled (deg)	3,984,533
Direction Changes (#)	140,252
Start/Stop Cycles (#)	181,707
Run Time (min)	52,596

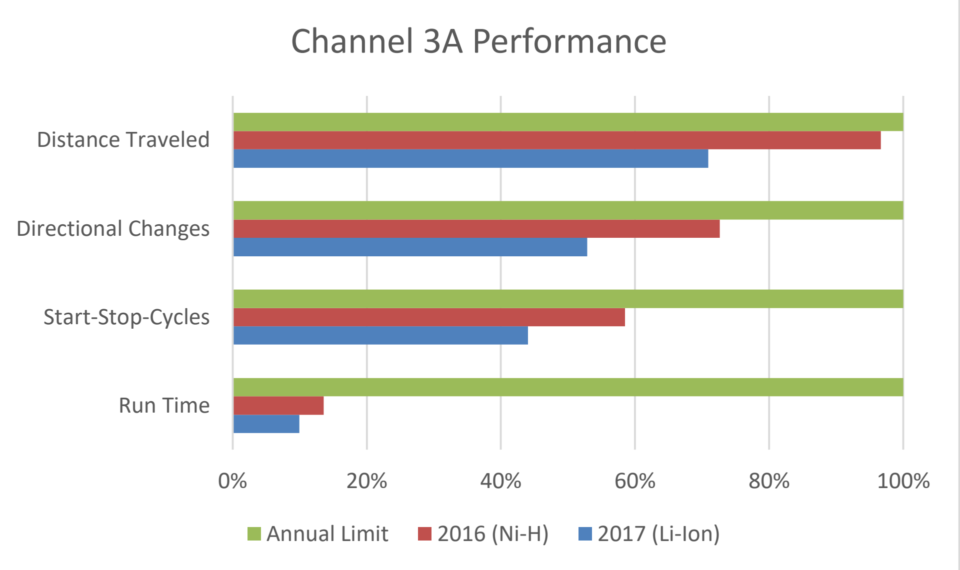
- FCV position sensor reading is downlinked in telemetry every 10 seconds
- Position analyzed to evaluate parameters against limits
  - Integrated to calculate degrees travelled
  - Consecutive points compared to find direction changes and stop-start events
  - Run time based on known turn rate of 9 deg/sec

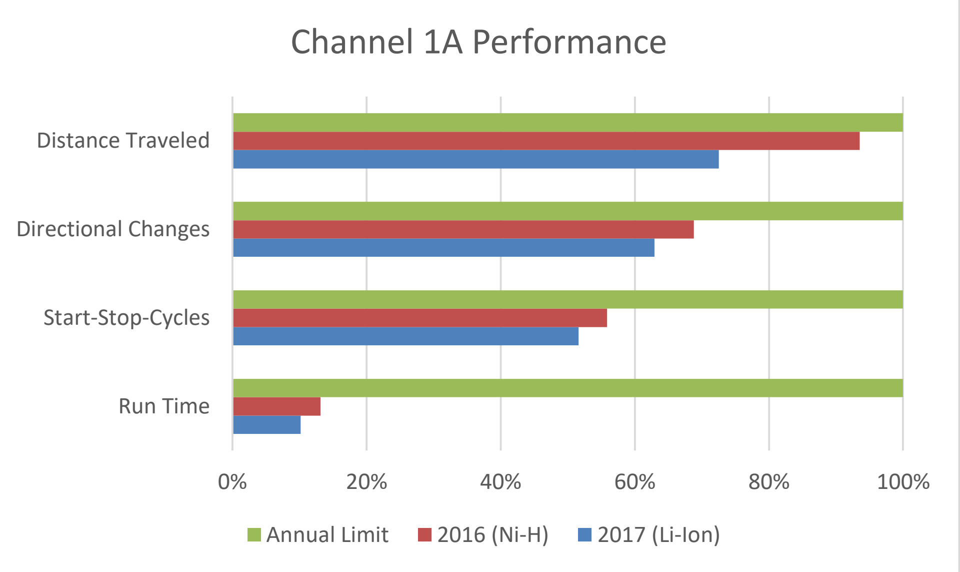
Observed FCV Motion Over First Year of Operations

Two sets of LI batteries were installed early 2017: into power channels 1A and 3A

With LI:

- Both channels are showing less activity on average
- On a given day, the FCV can be more busy under LI
- FCV motion after a year of on-orbit operations meets requirements
- Plan is to install LI batteries into the three other IEAs using the same FCV algorithm and settings





Conclusion

- LI batteries were developed to replace the original Ni-H2 batteries on ISS
- The PVTCS thermally conditions the batteries and associated equipment
- PVTCS thermal control algorithms were updated to accommodate LI requirements while still meeting all other requirements
- FCV motion is driven by the thermal control algorithm
- Development analysis predicted satisfactory FCV duty cycle behavior
- The first two sets of LI batteries were installed on ISS in early 2017
- Study of one year of on-orbit performance indicates satisfactory FCV duty cycle behavior