

# The International Space Station 2B Photovoltaic Thermal Control System (PVTCS) Leak: An Operational History

Anthony N. Vareha<sup>1</sup>

NASA Lyndon B. Johnson Space Center, Houston, Texas, USA

As early as 2004, the Photovoltaic Thermal Control System (PVTCS) for the International Space Station's 2B electrical power channel began slowly leaking ammonia overboard. Initially, the operations strategy was "feed the leak," a strategy successfully put into action via Extra Vehicular Activity (EVA) during the STS-134 Space Shuttle mission. This recharge was to have allowed for continued power channel operation into 2014 or 2015, at which point another EVA would have been required. In mid-2012, the leak rate increased from 1.5lbm/year to approximately 5lbm/year. As a result, an EVA was planned and executed within a 5 week timeframe to drastically alter the architecture of the PVTCS via connection to an adjacent dormant thermal control system. This EVA, US EVA 20, was successfully executed on November 1, 2012 and left the 2B PVTCS in a configuration where the system was now being adequately cooled via a different radiator than what the system was designed to utilize. Data monitoring over the next several months showed that the isolated radiator had not been leaking, and the system itself continued to leak steadily until May 9th, 2013. It was on this day that the ISS crew noticed the visible presence of ammonia crystals escaping from the 2B channel's truss segment, signifying a rapid acceleration of the leak from 5lbm/year to 5lbm/day. Within 48 hours of the crew noticing the leak, US EVA 21 was in progress to replace the coolant pump – the only remaining replaceable leak source. This was successful, and telemetry monitoring has shown that indeed the coolant pump was the leak source and was thus isolated from the running 2B PVTCS. This paper will explore the management of the 2B PVTCS leak from the operations perspective.

## Nomenclature

$\beta$	= Solar Beta Angle
$NH_3$	= Anhydrous Ammonia
DC	= Direct Current

## I. Introduction: Space Station Electrical Power and the PVTCS

THE eight primary power channels of the International Space Station (ISS) Electrical Power System (EPS), corresponding to the eight solar array wings on the station's truss, are the core of the United States Orbital Segment (USOS) power architecture. One of the primary purposes of the ISS integrated truss structure is to support these eight power channels, with two channels located on each of the four Photovoltaic Modules (PVMs). PVMs are named based on their port or starboard truss position and distance from ISS central

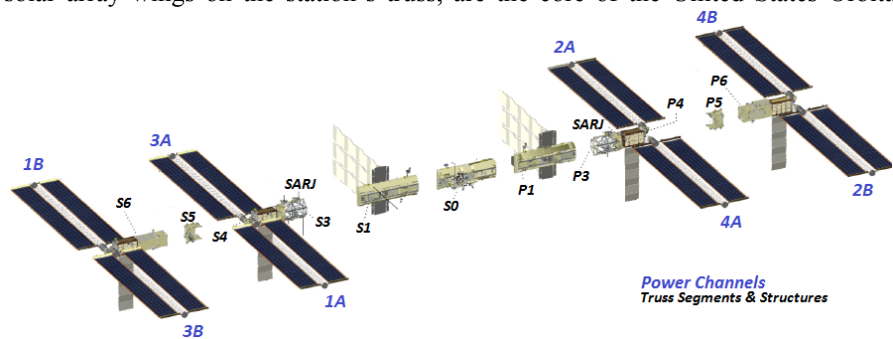


Figure 1. ISS Truss Schematic.

<sup>1</sup> International Space Station SPARTAN Flight Controller, Mission Operations Directorate, Electrical and Thermal Systems Group, DI4

modules, and each supports two power channels as shown in Figure 1. Each PVM contains the components needed to provide 150-160V DC power to downstream systems and payloads, and batteries to allow uninterrupted power through the ISS's orbital eclipse/insolation cycle. All USOS EPS and NH<sub>3</sub> cooling is the operational responsibility of the Station Power, ARticipation, Thermal, and ANalysis (SPARTAN) officer within NASA's Mission Operations Directorate (MOD), located at the Mission Control Center in Houston (MCC-H).

### A. Photovoltaic Thermal Control System (PVTCS)

As battery discharge is an exothermic reaction, active cooling is necessary to keep batteries below upper operating temperature limits. Cooling is also necessary for the various electrical components on the PVM involved in power routing and DC-to-DC voltage conversion. This active cooling is provided by the circulation of NH<sub>3</sub> in the Photovoltaic Thermal Control System (PVTCS), which uses a Pump Flow Control Subassembly (PFCS) orbit replaceable unit (ORU) to circulate coolant through the Integrated Equipment Assembly (IEA) onto which the EPS ORUs are attached. The PFCS contains two pumps for redundancy, with only one pump active at a time. The PFCS also contains a Flow Control Valve (FCV) for temperature control. The FCV rotates as needed to force NH<sub>3</sub> to either bypass or flow through the Photovoltaic Radiator (PVR) based on the battery temperatures. Though each channel's PVTCS loop is independent, both loops on a given PVM flow through the same PVR ORU. At time of launch, each PVTCS contains approximately 53lbm of NH<sub>3</sub>, of which approximately 13lbm is surplus to provide for some amount of leakage. Figure 2 shows a schematic of the PVTCS.

### B. EPS Redundancy

The electrical power system's eight-channel architecture allows for great flexibility in terms of response to component malfunctions. Loss of a power channel can result from a variety of malfunctions occurring in a number of ORUs or in the wiring between them. In the case of an electrical short, channel loss may be instantaneous. In the case of PVTCS loss, channel loss will occur within hours as the channel batteries reach their maximum operating temperature.

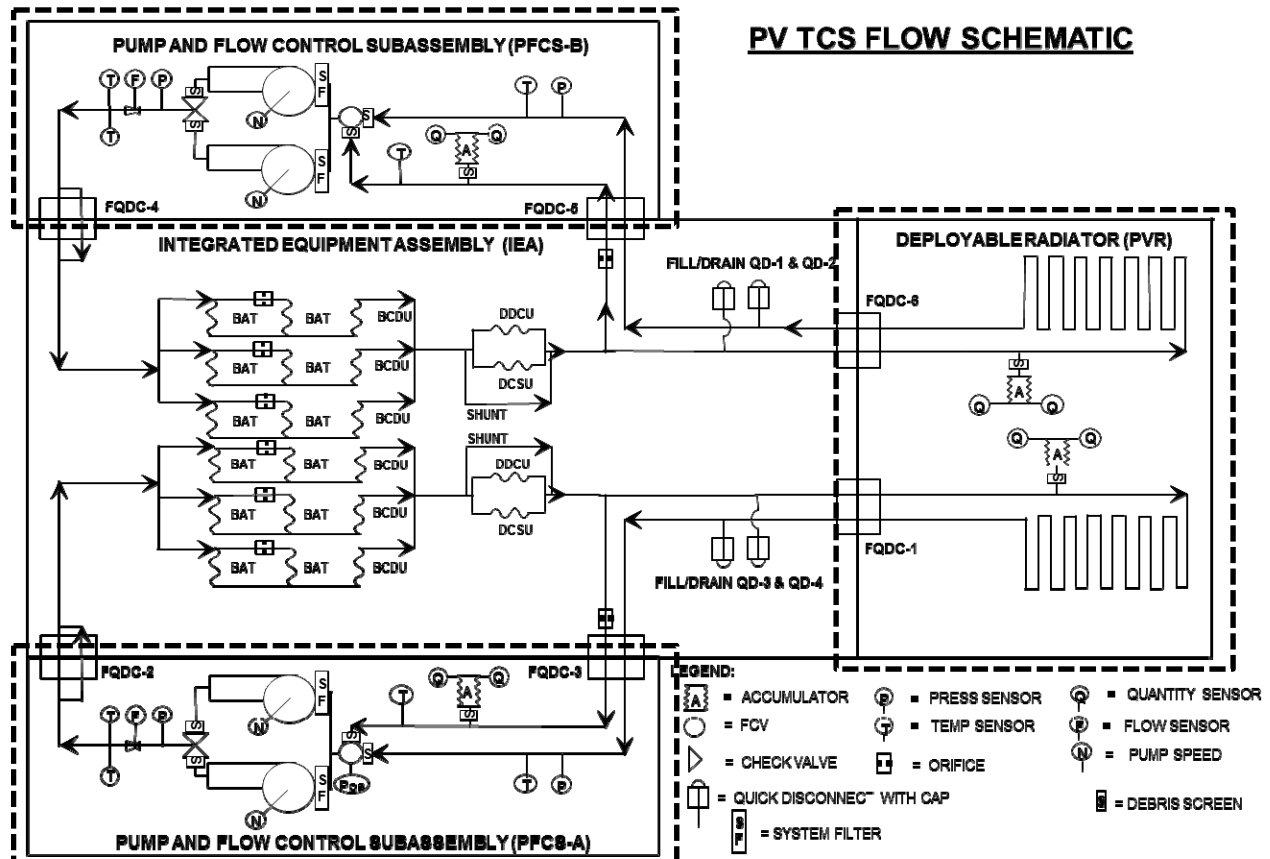


Figure 2. PVTCS Schematic.<sup>1</sup> For the P6 PVM, the 2B PVTCS would be the upper loop as shown, with 4B below. Orbit Replaceable Units (ORUs) are denoted by dashed lines.

The failure of any single power channel can be allayed by handing over that channel's end user loads to another channel via such EPS ORUs as the Main Bus Switching Unit (MBSU). For instance, in response to a malfunction in late 2012 of the 3A channel, a relay was commanded closed within MBSU 3 to provide power to all of channel 3A's loads from the 3B channel. This, combined with some parallel power architecture downstream of the MBSUs allows for the operational flexibility to sustain the loads of a lost power channel while not overtaxing any other channel.

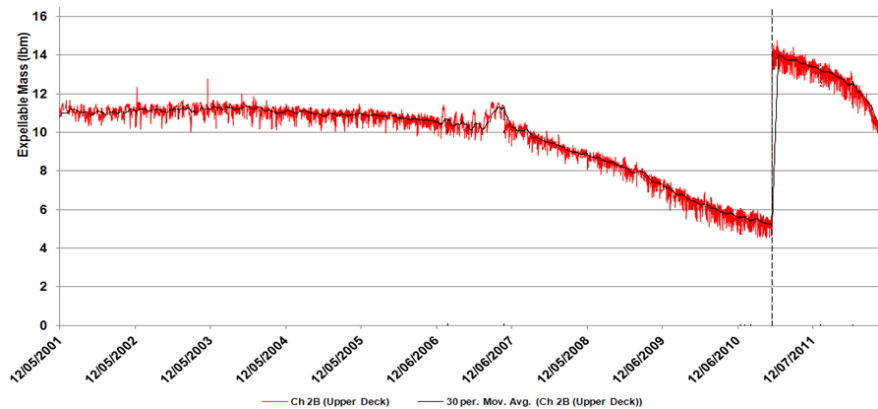
The core functions of the USOS are divided between three power channels: 1A, 1B, and 2B. These core functions include the avionics and thermal control of the US Lab module – both the internal water cooling and the external NH<sub>3</sub> cooling. 2B is the only channel which powers both an internal thermal control loop as well as an external loop. 2B also powers one of two S-band communication systems which is the primary communication path between ISS and MCC-H for voice, commanding, and telemetry. Therefore, the 2B channel is arguably the most critical power channel on ISS.

Loss of the 2B channel alone is not catastrophic; loads can be shifted, primarily to the 2A channel. However, the presence of so much critical equipment on the 2B channel puts a large power demand on whatever channel or channels would end up supporting its loads. The aggregate effect of a long-term loss of the 2B channel is a loss of redundancy and a decreased capability to respond to any subsequent ISS failure. Furthermore, though the loads can be shifted, the overall supply of power to the USOS is reduced by approximately 12.5%\*. These reductions are exaggerated whenever solar arrays are not autotracking the sun such as when they are positioned for vehicle dockings/undockings, thruster activity, etc.

## II. Identification of 2B Ammonia Leak

Determining the trend of fluid mass in an ISS NH<sub>3</sub> system is not a straightforward task, as the system provides data from a limited set of temperature, pressure, and fluid quantity sensors. This, combined with the effects of orbital cycles, perturbations of FCV operation, and the -75° to +75° variance of the solar β angle, leaves the difficulty in trending a fluid leak inversely proportional to the size of any such leak. Nevertheless, by the middle of 2008, Boeing thermal systems engineers noticed that the 2B channel's PVTCS had been losing NH<sub>3</sub> mass at a rate of approximately 0.75lbm/yr to 1.5lbm/yr since 2004 (see Figure 3). If enough NH<sub>3</sub> were to leak out, a Fault Detection Isolation and Recovery (FDIR) software algorithm would automatically shut off the pump to prevent pump cavitation and damage.

A leak of this size was far too small to be detected visually, as the orifice associated with such a massflow would be microscopic. Therefore, a "feed the leak" strategy was agreed to by the ISS Program, whereby spacewalks would occur every few years for the purpose of topping off the NH<sub>3</sub> reserve. By the middle of 2009 the ISS Program determined that the first such refill would occur during the STS-134 mission, also known as ISS flight ULF-6, which at the time was scheduled for mid-2010. This would allow the refill to be completed ahead of the 2B PVTCS reaching its automated FDIR shutdown point due to low quantity levels, which was estimated to occur in the middle of 2013.



**Figure 3. Expellable PVTCS 2B fluid mass (lbm), 2001-2012.** *Expellable mass of 0 represents the point at which the 2B PVTCS would need to be shut down to prevent pump cavitation. Mass is calculated based on a small set of temperature, pressure, and fluid quantity sensors located within the PVTCS, and can be biased by thermal environments, attitude, and whether or not the PVTCS is unpowered (as it was for a time in late 2007 when the P6 truss was relocated). The dotted line is the STS-134 PVTCS refill described in section III. Note rate increase in 2012 as described in section IV.*

This would allow the refill to be completed ahead of the 2B PVTCS reaching its automated FDIR shutdown point due to low quantity levels, which was estimated to occur in the middle of 2013.

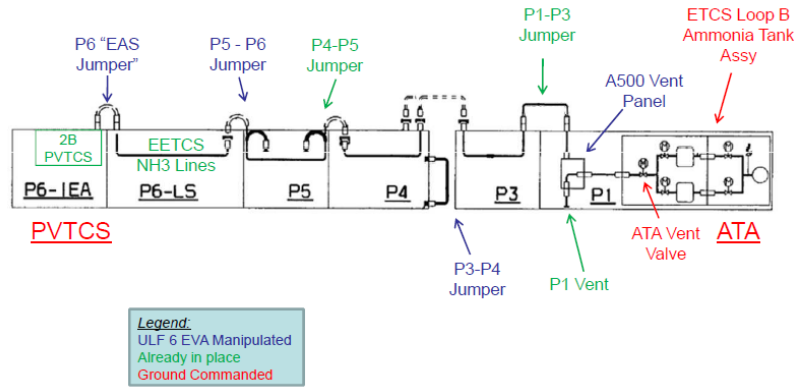
\* As the 2B solar array, along with 4B, has been on orbit the longest and has degraded with time, total power capability is slightly less than 12.5% of total USOS capability.

### III. PVTCS Refill Concept and Execution

#### A. Refill Architecture

As the leak of a PVTCS was a known possibility from the early days of ISS design, the integrated truss structure was designed to facilitate the refilling of a PVTCS from the much larger NH<sub>3</sub> stores of the External Thermal Control System (ETCS) via a series of in-situ pipes and EVA-installed jumpers (see Figure 4).

The ETCS is the NH<sub>3</sub> system responsible for the cooling of the habitable modules of the USOS, in addition to a number of critical EPS ORUs located on the truss itself. Compared to the eight PVTCS loops, each with ~55lbm of



**Figure 4. PVTCS Refill Pipeline schematic**

between either ETCS and any PVTCS, as the constantly-rotating Solar Alpha Rotary Joint (SARJ) is in between. The refill pipeline for the P6 PVTCS starts at EVA-configured fluid jumper panel A500. At this panel located on the P1 truss, a small 0.25" diameter, 16" long fluid jumper can connect any two of the three ports: the supply from the mechanical ATA overboard vent valve, the path to an overboard vent, and the refill pipeline.

Outboard of this plate, the in-situ tubing continues to a male quick disconnect (QD) at the outboard end of the P1 truss segment. From here, another EVA-installed jumper connects to a similar QD on the inboard end of the P3 truss segment (there is no P2 truss segment). This connection was already in place at the start of STS-134, as the connection of this and similar truss-to-truss jumpers had been completed on previous EVAs. A similar hardline/jumper configuration connects P4 to P5.

Immediately inboard of the PVTCS is a section of P6 called the long spacer. The long spacer contains the unique architecture of the Early External Thermal Control System (EETCS), which was designed into the P6 truss to support US Lab cooling from 2000-2006 before the ETCS was assembled with the launch of the S0, S1, and P1 trusses<sup>1</sup>. The EETCS fluid system is separate from P6's two PVTCSs, and utilizes two of its own radiators, deployed orthogonally to the P6 PVTCS radiator.

From its launch in 2000 until 2007, the P6 truss sat atop the ISS centerline versus its current position as the most outboard port segment of the truss. The EETCS was deactivated in 2007 when the ETCS was activated to provide heat rejection for the US Lab. In October 2007, with the port-side truss assembled out to P5, the P6 truss was robotically conveyed from its central position near the US Lab out to the end of P5 where it remains today. The EETCS also acts as one of the final segments of NH<sub>3</sub> travel during a P6 PVTCS refill, as some of the tubing of the dormant EETCS is utilized as an NH<sub>3</sub> passage. From P5, NH<sub>3</sub> flows through a fluid jumper into the P6 EETCS lines, and then through a final jumper into the P6 PVTCS known as the Early Ammonia Servicer (EAS) jumper (described in section IV).

With much of the architecture in place by design or as a result of EVAs leading up to an eventual PVTCS refill (see Figure 4), the remaining tasks for the STS-134/ULF-6 crew to enable a refill were to:

- Vent the nitrogen pad from the refill pipeline
- Configure the A500 panel for the PVTCS fill (and return to normal at EVA completion)
- Connect P3 to P4 via a jumper across the SARJ, which would be locked for the EVA
- Connect P5 to the EETCS
- Connect the EETCS to the 2B PVTCS via the EAS jumper

Once the desired connections were in place, MCC-H could commence the refill operation via ground-commanded valve operation.

### **B. From Refill Design to Execution**

When the MOD team was notified in 2009 that the PVTCS 2B refill was being added to the STS-134 task list, the assigned flight control teams immediately started examining the never-before-used refill architecture. The concept of the refill was straightforward: connect the large ETCS to the small PVTCS via a series of jumpers, and use regulated nitrogen pressure to command the proper amount of ammonia transfer. However, the MOD team quickly determined that the PVTCS refill would be an extremely dynamic operation.

Over the 18 months before the STS-134 mission, the MOD flight controllers responsible for the ETCS and PVTCS collaborated with thermal engineering teams, spacewalk officers, astronaut crewmembers, and safety & mission assurance personnel to develop the nominal and contingency procedures which would be utilized to execute the design concept of the PVTCS refill pipeline. The procedures would have to ensure a precise fill, as underfilling would require a refill sooner, and overfilling could potentially lead to overpressurization of the PVTCS in certain thermal environments. Also, it was critical that the fill be executed in such a way to mitigate the risk of the crew spacesuits being contaminated with the toxic  $\text{NH}_3$  when ingressing the habitable modules at the end of the EVA. Furthermore, the risks to the onboard thermal systems themselves were evaluated, as a leak or malfunction of any component could have tremendous impact on future ISS operations.

The most significant constraint from the thermal systems perspective was that while the ETCS was in fluid contact with the EETCS or PVTCS, at least one closed valve needed to separate the PVTCS from the nitrogen supply tank. This constraint was designed to mitigate the risk that a sudden failure of the GPRV, which normally keeps ETCS loop pressures above 2000kPa, would cause pressures to increase above the 1551kPa maximum operating pressure of the EETCS & PVTCS. This constraint drove most of the complexity of the refill procedure. As a result, it was decided that a known safe pressure would be set in the ATA at the start of the EVA, and this pressure would be used once the pipeline was assembled to push  $\text{NH}_3$  into the PVTCS. If the end pressure was too much, it could simply be vented by the GPRV as long as the nitrogen supply tank was sealed off by closing the N2 Supply Valve – similar to the procedure performed when filling an automobile tire. If the pressure was too little, a 20-minute cycle of ground commands would be needed to isolate the ATA from the refill pipeline, repressurize the ATA from the NTA, isolate the nitrogen tank, and open the ATA to the refill pipeline once again.

Another concern, which threatened to complicate the EVA timeline, was with hydraulic isolation of the pipeline. Following the PVTCS refill, the stretch of the refill pipeline from the P1 truss to the P5/EETCS interface, as well as the jumper between the EETCS and PVTCS, would be vented. The lack of an accumulator to provide hydraulic compliance on either of these pipeline sections meant that venting was required for concern of overpressurizing and bursting the lines in the likely event that the truss was subjected to a warmer thermal environment. However, this venting also required that for some short period, the lines would have to be isolated before being vented. Normally, this would require that both pipeline sections be vented during orbital eclipse; however, placing such a requirement on an EVA timeline is undesirable as it is inefficient to pull a crewmember away from a task they are working on to go execute a separate, time-critical task at a different worksite. Therefore, MOD asked thermal engineers to perform analysis to determine, worst-case, how long it would take the isolated pipeline in direct sun to warm up above maximum certified pressure. Engineers deemed it acceptable to isolate the P1-P5 pipeline for 2.5 minutes even in insolation.

### **C. The PVTCS Refill EVA**

EVA 2 of STS-134 took place on May 21<sup>st</sup> of 2011. The ISS thermal system configuration at the start of the EVA was with the ETCS Loop B ATA isolated from the main circuit of the loop, and ATA Tank 2 pressurized to 1551kPa in preparation for the fill. The PVTCS was operating nominally, with the exception that its FCV was commanded to hold a slightly cold-biased position rather than engage in closed-loop control. This was an effort to keep the PVTCS fluid dynamics in a steady-state configuration.

Just after 0709 GMT, the refill operation began with the ground-commanded opening of the ATA vent valve to pressurize the pipeline from P1 to P5. After confirming that ATA fluid quantities quickly stabilized and that the pipeline was not leaking, the EETCS was opened to the pipeline when EVA crew opened the P5/EETCS connection. Again, after watching the fluid quantities settle (this time with the added telemetry of the EETCS accumulator sensors) the jumper to the PVTCS was opened. Within minutes, PVTCS pressure increased from 900kPa at the pump inlet to over 1200kPa, and a 2B PVTCS fluid quantity sensor showed an increase of over 30%. After the thermal systems officer, per thermal engineering request, utilized the GPRV to slightly reduce the pipeline pressure (and, with it, the PVTCS pressure), the EVA crew was directed to disconnect the PVTCS from the pipeline. This

was performed at 0754GMT, less than an hour from the start of the fill. Later computations showed that a total of 8.57lbm of NH<sub>3</sub> was transferred into the PVTCS, just 0.16lbm short of the targeted fill mass. The refill was a tremendous success, and the 2B PVTCS was returned to nominal operation by the end of the EVA. Assuming an unchanged leak rate, the system could operate for over 4 years before needing another refill.

## **IV. 2012 Leak Rate Increase & US EVA 20**

### **A. EVA Necessity**

In September 2012, active thermal engineers determined from their long-term PVTCS 2B mass trending that its leak rate had increased, perhaps fourfold, and that the leak rate increase may be exponential. Due to the “noise” inherent in plotting the PVTCS mass this leak rate increase was only confirmed months after it began, and could not be precisely quantified (see Figure 3). Nevertheless, if the exponential trend were to continue, the 2B PVTCS would likely leak out by the start of 2013.

EVA planning began almost immediately. Crew rotation and solar beta constraints made late October/early November 2012 the desired time for an EVA. The first decision to be made was whether to perform a PVTCS refill to try to sustain operations until a new crew arrived in 2013, or to attempt a troubleshooting EVA. Almost immediately, a refill was deemed to be inappropriate for a crew who had never rehearsed such an operation on the ground. Though it could certainly be done, the likelihood was that a crew without ground training would require 2 EVAs, not 1, to perform the task. The decision was made to troubleshoot.

Though it was possible to determine with some certainty where the leak was by isolating the three parts of the PVTCS - PFCS, PVR, and irreplaceable hardlines/coldplates - and monitoring them for leaks, the isolation would require that the 2B PVTCS remain offline for an extended period. This was deemed undesirable due to the criticality of the 2B channel loads. Another early idea was to simply replace the PFCS; however any gains in EVA simplicity would be overshadowed if the PVR was the leak source, a leak source that would have quickly depleted the system reserve.

### **B. Proposed System Architecture Reconfiguration**

To allow the channel 2B PVTCS to keep running while attempting to isolate the leak source, ISS engineers and operations personnel crafted a plan to utilize a unique capability of the P6 truss segment. The 2B PVTCS would be cross-connected with the adjacent decommissioned EETCS via two EAS jumpers, and one of the EETCS radiators would be redeployed after 6 years of dormancy. In this configuration, the 2B flowpath within the P6 PVR could be isolated while the Trailing Thermal Control Radiator (TTCR) of the EETCS provided cooling to channel 2B. This configuration is shown in Figure 5.

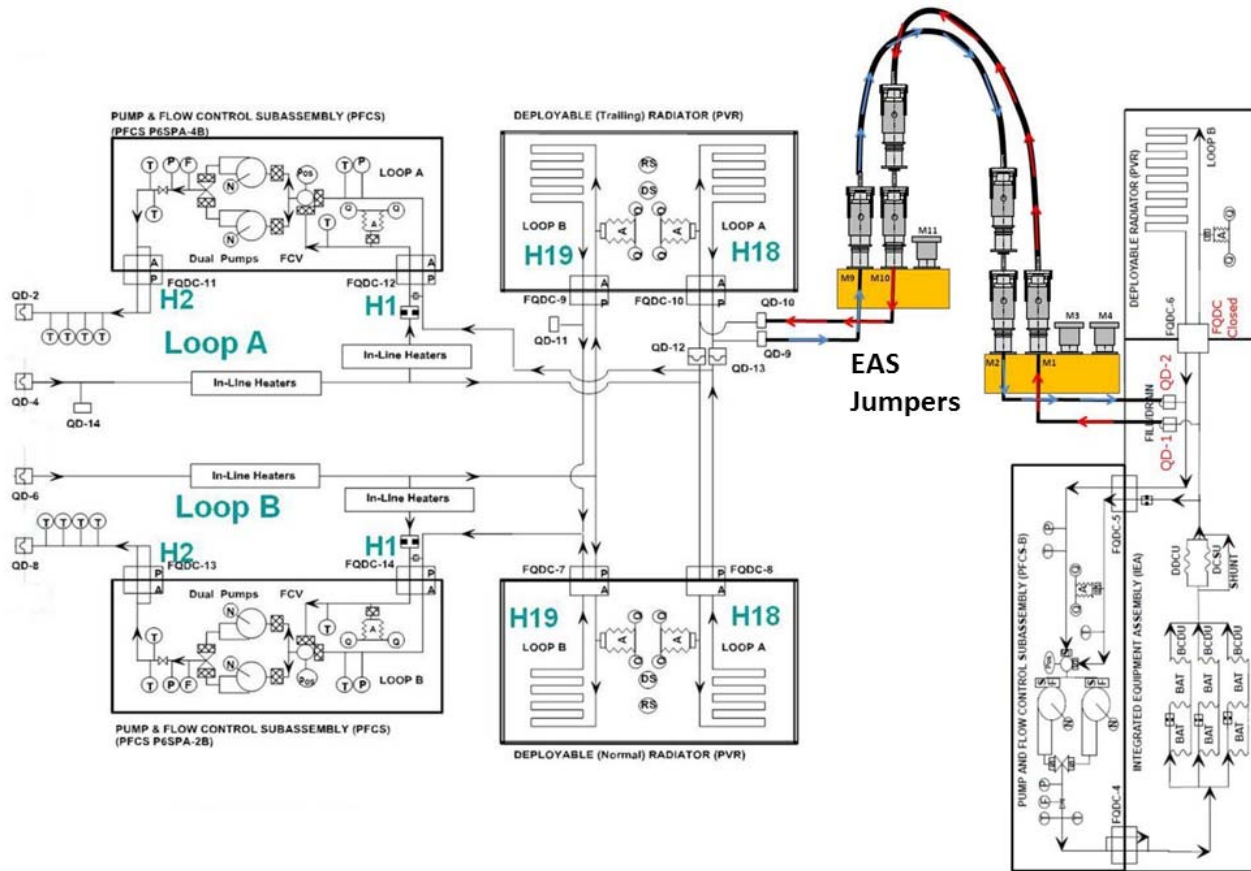
That this cross-connection capability exists at all is a testament to operational foresight. In the late 1990's, the ISS Program asked MOD to develop some suggestions for hardware which could inexpensively be added to the ISS to mitigate potential failures instead of requisitioning additional expensive spare ORUs. The goal was to make the ISS a more resilient vehicle, better able to sustain operation if critical equipment failed, especially in the early stages of ISS construction. Until STS-115 launched the P4 PVM, the USOS only had two primary power channels: 2B and 4B. If one of these channels were to fail, the difficulty of assembling the ISS would increase dramatically. One such potential failure was the leak of one of the two PVTCS loops.

In order to help ensure electrical power system reliability in the early period of ISS assembly, the EAS was designed to be an EVA-operated pressurized NH<sub>3</sub> tank to refill a PVTCS after a leak was isolated. If such a leak was determined to be in one of the three radiators on the P6 truss – the PVR, the TTCR, or the Starboard Thermal Control Radiator (STCR) – that radiator would be isolated and the remainder of the loop would be refilled from the EAS. After the refill, two flexhoses (the EAS jumpers) would be put in place to carry the PVTCS NH<sub>3</sub> over to the EETCS Loop A radiators. This EAS implementation strategy was developed after construction of the P6 truss had already begun, and thus utilized quick disconnect ports already in place for fill-and-drain purposes.

Though the EAS was never needed and was jettisoned from station in 2007 after the STS-115 mission was complete, the EAS jumpers remained. Their first use was in 2011 when one was used as the final connection to the PVTCS during the 2B refill, and their full capability was realized in 2012 for EVA 21 when the EAS jumpers connected the ailing 2B PVTCS to the dormant EETCS. Though cross-connecting the PVTCS to flow through the EETCS was an established concept, the 5 weeks of preparation before EVA 20 were spent not just choreographing the spacewalk, but also involved a tremendous effort from thermal engineers to verify that the fluid dynamics of the



to-be-created “hybrid” system would allow for adequate cooling of the 2B EPS ORUs given the state of the ISS in 2013 in terms of power demand, vehicle attitude, and other operational constraints.



**Figure 5. Schematic of PVTCS/EETCS “Hybrid Config”.** The 2B lines of the P6 PVR, shown top right, are isolated. Warm  $NH_3$  leaves the 2B PVTCS out of QD-1, through one of the EAS jumpers, and enters EETCS Loop A via QD-10. From here, the  $NH_3$  arrives at a T-junction. Half of the  $NH_3$  flows through the deployed Trailing Thermal Control Radiator (TTCR, shown at top), while half flows through the retracted Starboard Thermal Control Radiator (STCR). Note that the radiator naming convention is based on its original position atop the station centerline. The 2B PFCS, at right, contains the only running pump – the EETCS Loop A and B PFCSs are powered, but their pumps are off. All of EETCS Loop B is stagnant.

### C. US EVA 20 – November 1<sup>st</sup>, 2012

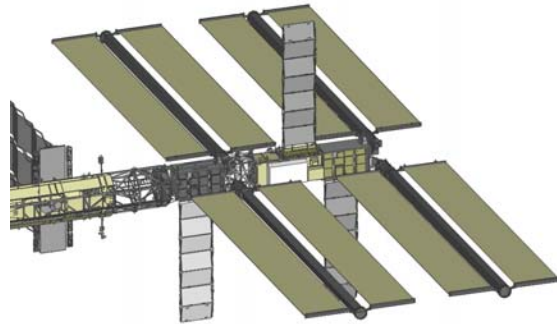
US EVA 20 was executed to put the above plan into action. First, a fluid connector valve was closed to isolate the channel 2B flowpath within the P6 PVR. Next, the EAS jumpers were configured so that PVTCS  $NH_3$  which would normally flow to the PVR would be routed out through the jumper over to the EETCS with its to-be-deployed TTCR. Finally, the TTCR insulation shroud was removed and the TTCR was uncinched. Once the crew was clear of the radiator, SPARTAN successfully commanded deployment of the TTCR. The STCR remained retracted and covered by insulation; deployment was not an option due to interference with one of the solar arrays of the P4 truss (which was not an issue when P6 sat atop the vehicle centerline).

## V. Operating 2B PVTCS In the Post-EVA 20 “Hybrid Config”

In the months following EVA 20, MOD and engineering personnel determined that the 2B PVR lines were not leaking and the combined PV+EE system was continuing to leak at approximately the same rate seen before the EVA. As of early May 2013, data trending indicated that due to the added fluid mass from the EETCS, channel 2B

operation could continue until at least mid-2014 without EVA intervention. As far as day-to-day operations of the system, changes were few and minor, which meant retraining of ground operators was minimal.

The largest operational concern was how to protect the PVTCS pump against cavitation resulting from a sudden  $\text{NH}_3$  leak while not shutting down unnecessarily. Fault detection and isolation algorithms which monitored the accumulator quantities were smartly built with the ability for ground operators to force the software to ignore certain sensors – in this case, the sensors of the isolated radiator. However, the realities of this hybrid configuration were never assumed in the software design, and there was no automated FDIR leak algorithm which considered all of the relevant accumulators – the PFCS accumulator in the PVTCS, and the 3 accumulators in EETCS Loop A. If only the running pump's accumulator was accounted for, the leak algorithm would be too conservative and shut the pump off before truly needing to. This was a risk as the fluid dynamics of the system resulted in that particular accumulator having the lowest fluid levels. In response, MOD took advantage of a capability to create and utilize simple automated algorithms within station software known as Timeliner<sup>2</sup>. A Timeliner algorithm was created to monitor all of the accumulators of the hybrid system, and would deactivate the pump when 5 of 6 quantity sensors (some accumulators have 1 quantity sensor, some have 2) all fell below a safe level. From this point, the procedural response would be the same as for the leak of any other PVTCS.



**Figure 6. Overview of ISS port truss post EVA 20.** *The EETCS TCR is shown upwardly deployed, while the P4 and P6 PVRs are deployed downwards.*

System heat rejection capability was also altered with the change in 2B PVTCS architecture. The 2B PVTCS was made less capable to cool since  $\text{NH}_3$  flow was split between the deployed TCR and the retracted and non-cooling STCR. Furthermore, the TCR is deployed in the opposite direction of the PVRs (see Figure 6), and, with SARJ autotracking, the TCR's long axis pointed into the sun. The end result was that the PVTCS 2B FCV spent more time, on average, in the full cooling position than other channel PVTCS FCVs. MOD worked with engineering personnel to establish a protocol for responding to a scenario where channel 2B fluid became too warm to protect against pump cavitation. In this case, the pump would be shut down when net positive suction pressure fell below a certain value.

The 4B channel was affected by the 2B channel alterations, as channel 4B's  $\text{NH}_3$  had the P6 PVR all to itself and was therefore at risk of flowing colder  $\text{NH}_3$  than the lower operations limits of certain sensors. The bypass/flowthrough algorithm of the PVTCS FCVs on all channels result in very cold slugs of  $\text{NH}_3$  flowing through the system immediately following any FCV reposition to full cooling, and these slug temperatures fall very close to the lower FDIR limits. This problem was simply exacerbated on 4B to make an undertemp shutdown more likely in certain  $\beta$  and Port SARJ positioning combinations. In response, MOD worked with engineering personnel to establish a protocol to respond to a PVTCS undertemp by restarting the loop with the FCV at a fixed position. Meanwhile, engineering developed a matrix of  $\beta$  and Port SARJ positioning combinations which were most likely to trigger these events.

For both 2B and 4B, these temperature exceedances would only occur if the Port SARJ is not autotracking the sun, or if the ISS were in a non-standard attitude. To date, neither the channel 2B overtemp or 4B overtemp protocols have ever been needed as all assumptions are based on worst-case thermal environments and FCV timing.

There was also concern that the TCR and P6 PVR each had only one active flowpath, and one stagnant flowpath. If the remaining active flowpath stopped flowing due to a failure, there could be freezing or overpressure concerns. The freezing concern of the P6 PVR was sufficient for engineering to request that at certain high betas, in the event of a 4B PVTCS failure, the Port SARJ be biased by  $180^\circ$  to point the P6 PVR's long axis into the sun. In this case, power generation would not be affected as the solar array Beta Gimbal Assemblies (BGAs) would automatically flip themselves  $180^\circ$  to point towards the sun again. P4 PVR heat rejection would be reduced, too, by an acceptable amount. A similar protocol would need to be put into place any time a PVTCS loop was shut down for a long period, likely as the result of a loop failure.

In summary, a number of contingency procedures were updated for PVTCS operation as new constraints were discovered with the hybrid configuration, so as to fulfill MOD's goal of ensuring that an operator without intimate knowledge of the system's history would still have the needed information to respond to off-nominal situations.



## VI. May 2013 Visible Leak & US EVA 21

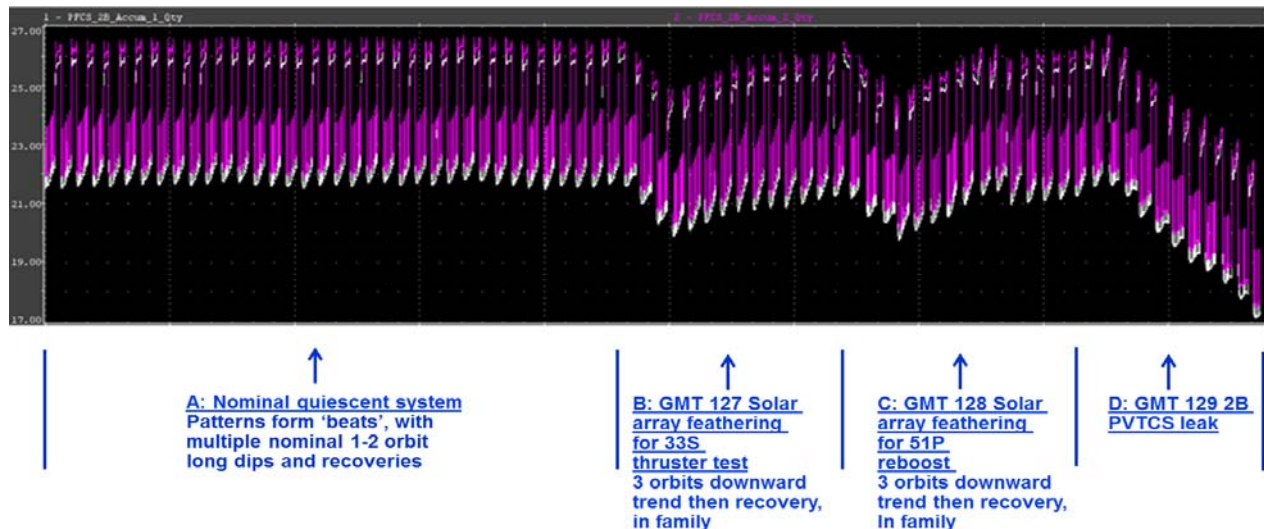
### A. Visible Leak and EVA Prep

On May 9<sup>th</sup>, 2013 (GMT 129) at approximately 10:30am CDT, ISS Commander Chris Hadfield called MCC-H, stating that the crew was seeing flakes emanating from the port truss. (Hadfield later stated that Pavel Vinogradov first saw the leak from the window of his sleeping quarters and notified the Commander of the “sparks” floating outside.) SPARTAN was also monitoring a decrease in 2B PVTCS quantity values at that time, but had initially assumed that the decrease was related to heat load reduction from a 2B battery capacity test in progress. Furthermore, the leak trend looked to be almost exactly the same type of trend commonly seen in the 2B post-EVA 20 configuration during any SARJ parking event – though the SARJs were autotracking at this time (see Figure 7). The crew was immediately asked to point a high-definition video camera at the leaking truss segment, as the JEM port side window provided optimal viewing.

Telemetry indicated a 5lbm/day leak, with automated shutdown action expected to occur within 24-48 hours when the 2B PFCS quantities would fall below 4%. The Timeliner bundle discussed previously was not yet onboard and therefore EETCS quantities were not a part of the leak shutdown algorithm.

Approximately 12 hours after the initial crew report of the leak, the relevant MBSU was configured to put all 2B loads onto the 2A channel. Once this was complete, the 2B PVTCS pump was commanded off. Within a number of hours, the visual appearance of flakes had stopped.

At a 3:00pm Failure Investigation Team meeting, the ISS Program Manager (after coordination with MOD EVA



**Figure 7. 2B PFCS Fluid Level (GMT 2013/124-129).** Y-axis is the fluid quantity as measured by two sensors within the 2B PFCS accumulator. Each ‘beat’ is approximately an orbit. Within an orbit, quantity is highest when the FCV is in full-radiator flow, due to the effects of line resistance across the hybrid system. Note the similarity of the pattern of the GMT129 leak to the two SARJ feathering events prior.

personnel) stated that the goal of the team would be to perform an EVA on May 11th. The EVA crew would replace the channel 2B PFCS, as this was the only possible remaining leak source in the 2B system having isolated the PVR on EVA 20. The only caveat was that a pump replacement would not be performed if it appeared to the crew that the leak source was obviously from the irreplaceable hardlines underneath the PFCS and EPS equipment.

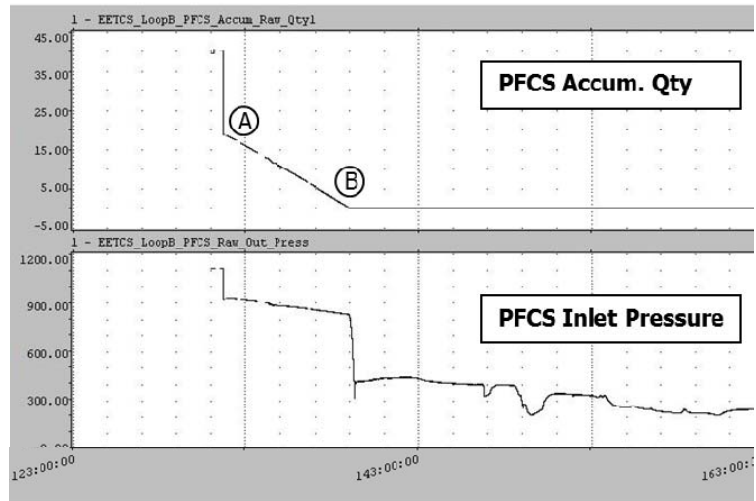
The desire for an unprecedentedly quick turnaround EVA was two-fold: First, 2 out of the 3 non-Russian crewmembers were slated to go home on May 13th on Soyuz 33S, leaving the ISS with no USOS-based EVA capability until Soyuz 35S docking in late May. Second, there was hope that if the crew was able to access the leak site within the short time frame, the NH<sub>3</sub> would remain a single-phase liquid for long enough to allow the crew to see NH<sub>3</sub> flakes and determine a possible leak source. In the end this hope was dashed as even though the NH<sub>3</sub> remained single-phase, the visible “snow” stopped within hours of 2B PVTCS shutdown. Other factors contributing to the decision to conduct an EVA on May 11<sup>th</sup> were the facts that the EVA was a fairly straightforward changeout of a single ORU with the spare PFCS located conveniently nearby, and the crewmembers were familiar with the P6 truss site from past experience.

## B. US EVA 21 – May 11<sup>th</sup>, 2013

Upon arriving at the P6 truss worksite, the crew found no evidence of NH<sub>3</sub> leakage – all ORUs and structures were reported to be “really, really clean” by EVA crewmember Chris Cassidy. Approximately 3 hours after airlock hatch open – and less than 49 hours from the time when the crew first notified MCC-H of a visible leak – the new pump was installed and powered on. As the spacewalk was running ahead of schedule, MOD decided, with engineering concurrence, that the pump would be activated while the crew was near the worksite. After pump activation, the crew stayed in position near the worksite for approximately 30 minutes looking for signs of a NH<sub>3</sub> leak, and saw nothing.

The installation of the new PFCS resulted in a slight increase in the total system fluid mass thanks to the stored NH<sub>3</sub> within that unit. Overall, however, system quantities were several percent lower than before the May 9th leak started.

From an operational standpoint, the PFCS removal & replacement resulted in a negligible amount of post-replacement retraining and procedure updates. The only additional operations work required was that new calibration data needed to be uploaded to software which communicated with the PFCS to allow it to properly read sensor data utilized in onboard FDIR algorithms. Until that calibration data was uplinked, operations personnel inhibited this software-based PFCS FDIR which protected against overtemperature and undertemperature exceedances. MOD & engineering personnel were comfortable with inhibiting these FDIR algorithms for the days it took the new calibrations to be uplinked, for a few reasons. First, as noted previously, PVTCS 2B was a warm-biased loop and undertemperature was seen as an extremely remote possibility. Overtemperature exceedance was possible, but if it would occur it would take several hours. Finally, the 2B channel was not yet providing electrical power to its normal downstream loads and therefore did not require quick response in the event of a pump failure in order to maintain critical avionics. MOD and engineering personnel thus decided that the benefits of providing 2B channel ORU cooling while awaiting calibration updates outweighed the risk of operating without software-based fault detection capability.



**Figure 8. PFCS S/N 4 telemetry after removal from 2B PVTCS (GMT 2013/123-163).** As the failed PFCS was transferred to a stowage site with data connectivity, MCC-H was able to monitor as the pump continued to lose ammonia. Point A shows the quantity level (%) and pressure (kPa) at the time of install during EVA 21. At point B, the PFCS accumulator bottoms out and the ammonia becomes a two-phase liquid-gas, with pressure dependent on thermal environment. Leakage continued until approximately GMT 180 when pressure dropped to vacuum.

## VII. Leak Resolution & Present System Status

Since the replacement of the 2B PFCS in May of 2013, 2B PVTCS system mass has stopped decreasing in any discernable fashion. Conveniently, the suspect PFCS was stowed in a position which provided data connectivity to its sensors, allowing ground personnel to observe as the ORU leaked out its remaining NH<sub>3</sub> content over the next several weeks, as shown in Figure 8.

There are no plans to return the leaked PFCS to Earth for a formal failure investigation to determine the root cause of the leak. Therefore, this PFCS is destined to remain onboard ISS as a failed ORU.

As of the writing of this document, the ISS Program has asked MOD and engineering personnel to create a plan to retract the TTCR and un-isolate the P6 PVR, as well as possibly performing another refill of the 2B PVTCS, in mid-2014. Doing so would reduce the risk to the TTCR, in its role as spare PVR, from micrometeoroid orbital debris. Such an EVA would effectively return the 2B PVTCS to a nominal configuration.

## VIII. Conclusion

From the start of the small leak as early as 2004, to the refill in 2011, to the drastic system architecture change of US EVA 20 in 2012, and finally the isolation and termination of the leak in May of 2013, it is remarkable to note that the 2B PVTCS remained active for all but the equivalent of a few days: during EVA 20, and during the large leak immediately before EVA 21. The forethought which went into the design of an in-situ PVTCS refill pathway, as well as the capabilities of the EAS and its jumpers, is impressive.

It must be noted, however, that the use of ground-commandable motorized valves in place of EVA-operated valves (and the EAS jumpers) could have theoretically prevented all but one of the EVAs executed to service the 2B PVTCS. When the leak was discovered in 2008, if the relevant valves had been ground-commandable, MCC-H could have isolated the 2B lines of the P6 PVR, cross-connected 2B to the EETCS, and monitored for years to see if the radiator or the PVTCS system was leaking. Eventually, the PFCS would have been deemed the likely culprit and would have been replaced via EVA. This admittedly is an operations-centric perspective and does not take into account the increased risk of leakage due to the valves nor any design challenges which would have been involved.

The overall lesson is in the importance of bringing the operations mindset into the design process as early in the project life cycle as possible to assist in evaluating the critical failure points not just in the final product, but in the assembly sequence as well. This lesson was on display for ISS by the design engineers who provided the PVTCS refill-from ETCS capability, and later by the MOD personnel who devised clever failure mitigations even after hardware was being constructed. The design process benefits from having a stakeholder with a different perspective to help create the final product and to understand its capabilities. In retrospect, this combination of versatile design and clever mitigation strategies have allowed the PVTCS to provide the reliability demanded by the ISS Program despite suffering an ongoing and potentially capability-limiting failure.

## Acknowledgments

The author would like to thank Mr. Bill Frank (United Space Alliance) for his assistance in data gathering and historical documentation. In addition, the author would like to acknowledge the outstanding work of the MOD and engineering teams who have kept the 2B PVTCS functional despite the leak, and whose efforts are summarized in this paper: From the SPARTAN group – Rami Al-Ayoubi, Stein Cantrell-Avloes, Dave Crook, Paul Gosling, Stephanie Perri, Michelle Zahner, and the rest of the SPARTAN and Power Resource Officer (PRO) team. From the Boeing Corporation – Casey Adams, David Fasig, Matthew Jurick, Aaron Simpson, Karen Thacker, and the entire Active Station Thermal Resources and Operation (ASTRO) team. From the Johnson Space Center's Engineering Directorate – Tim Bond, Richard Morton, Gary Rankin, and David Volkert. From the Flight Director office – Derek Hassmann, Mike Lammers, and Ed Van Cise. From MOD overall – Allison Bolinger, Christopher Crow, Jaclyn Kagey, and Victor Herod.

## References

<sup>1</sup>Reysa, R., and R. Thurman. "The International Space Station ECLS and thermal control systems-Overview." Sixth European Symposium on Space Environmental Control Systems. Vol. 400. 1997.

<sup>2</sup>Brown, Robert, et al. "Timeliner: Automating Procedures on the ISS." 2002 SpaceOps Conference, Houston, Texas. 2002.



# The ISS Photovoltaic Thermal Control System Leak

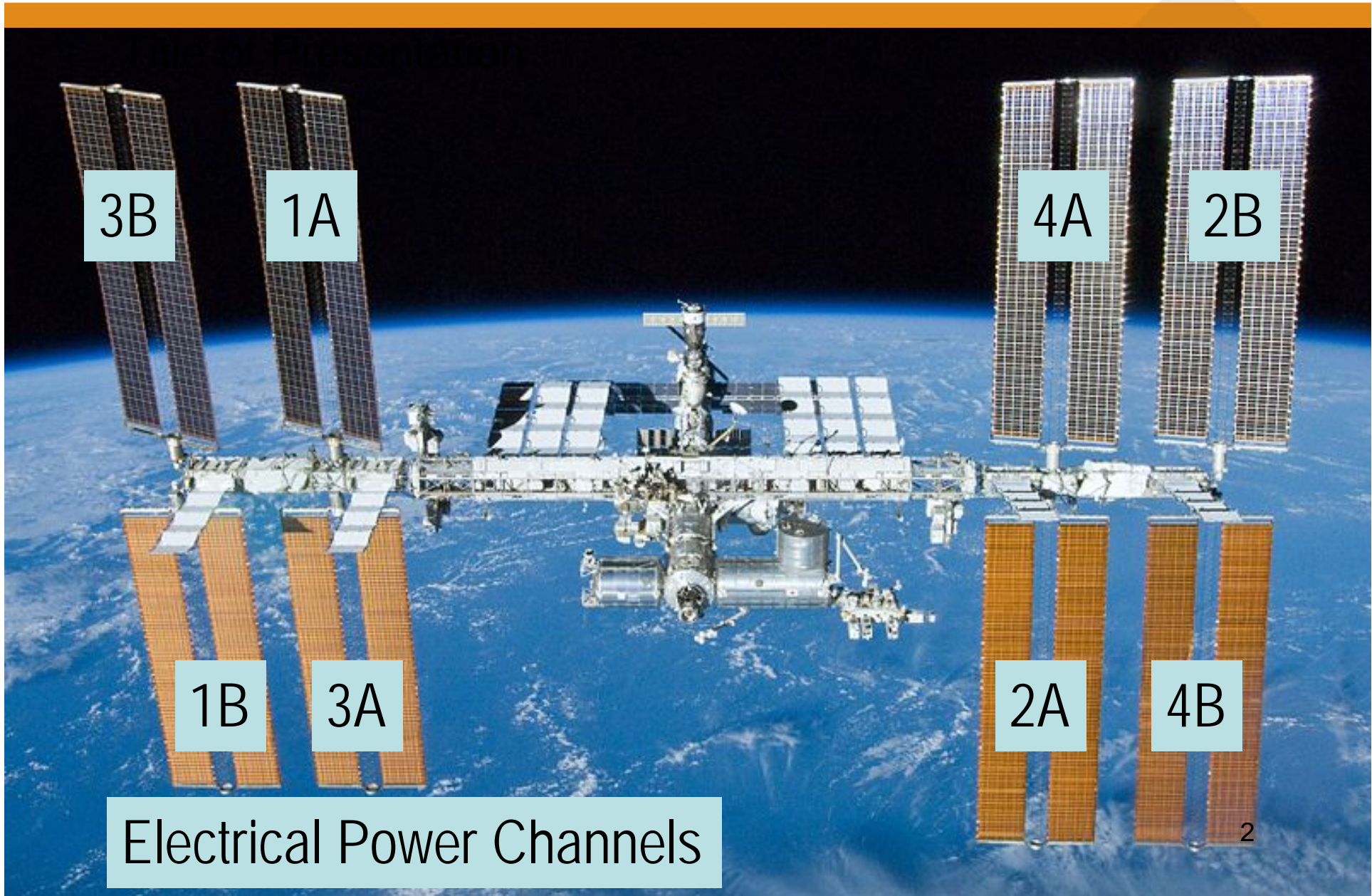
## An Operational History

Anthony Vareha

NASA/JSC SPARTAN (Station Power ARticulation Thermal and Analysis) Officer

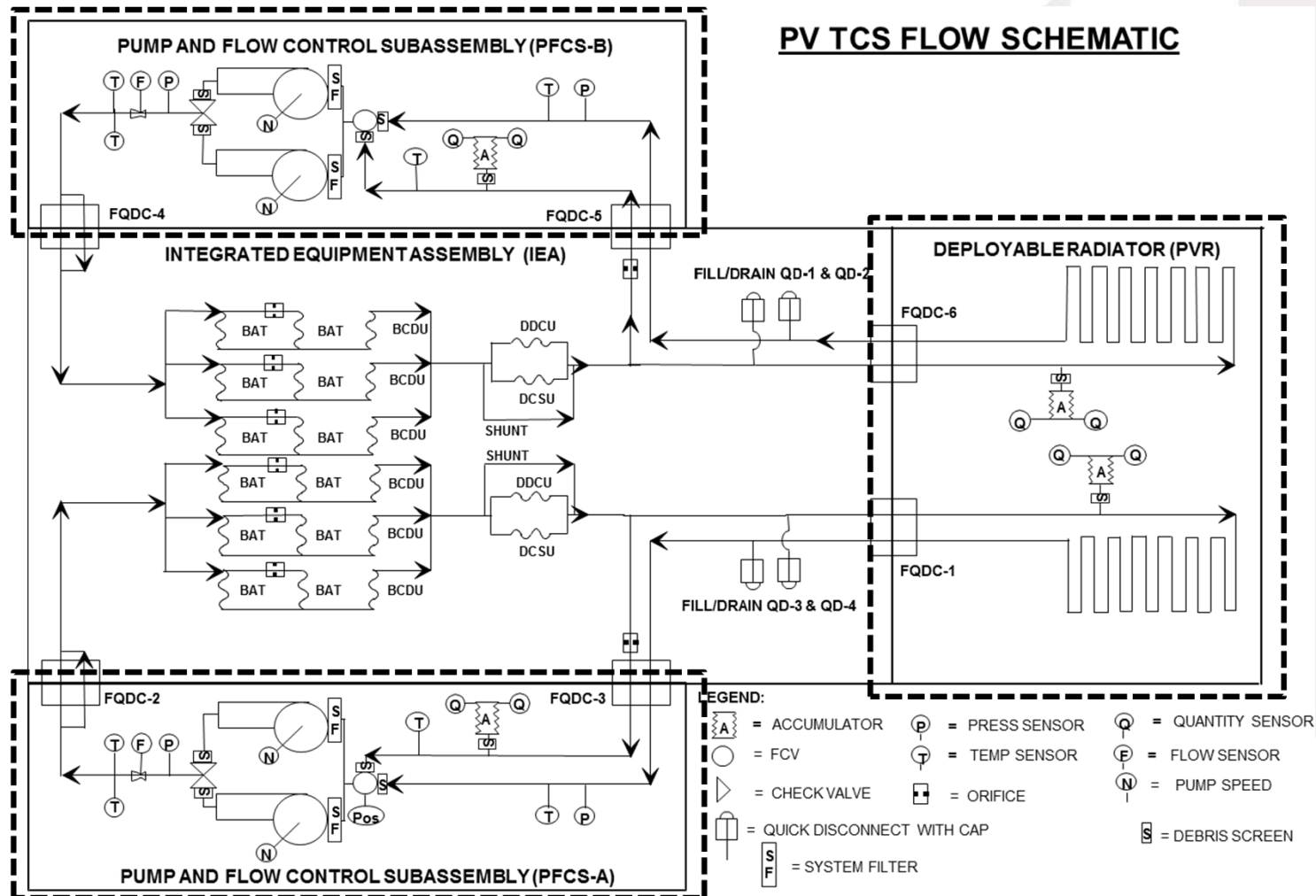
SpaceOps 2014, May 5<sup>th</sup> - 9<sup>th</sup> 2014, Pasadena





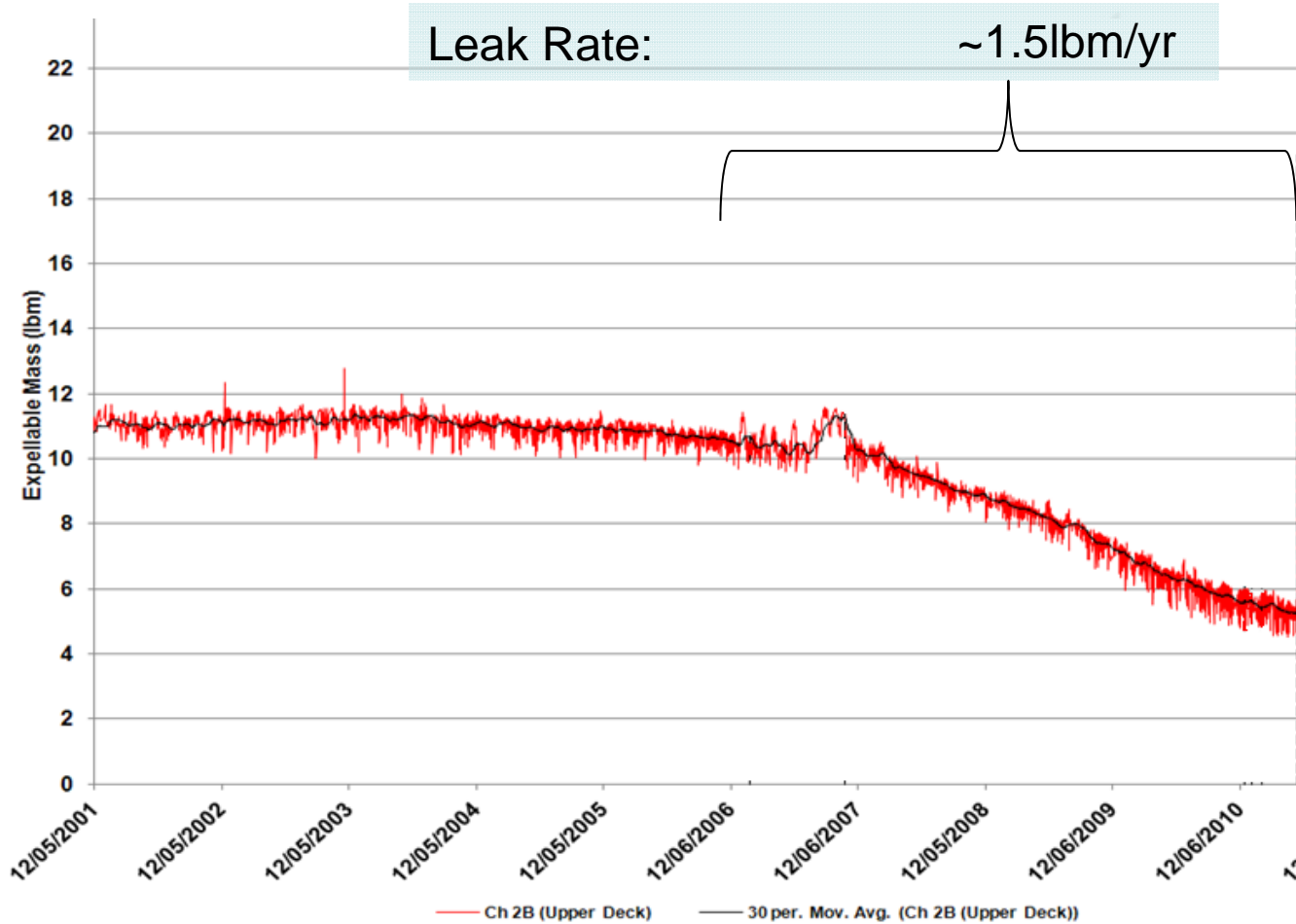
Electrical Power Channels

# The ISS Photovoltaic Thermal Control System Leak: An Operational History





# The ISS Photovoltaic Thermal Control System Leak: An Operational History



2B PVTCS NH<sub>3</sub> Mass vs. Time (2001-2011)

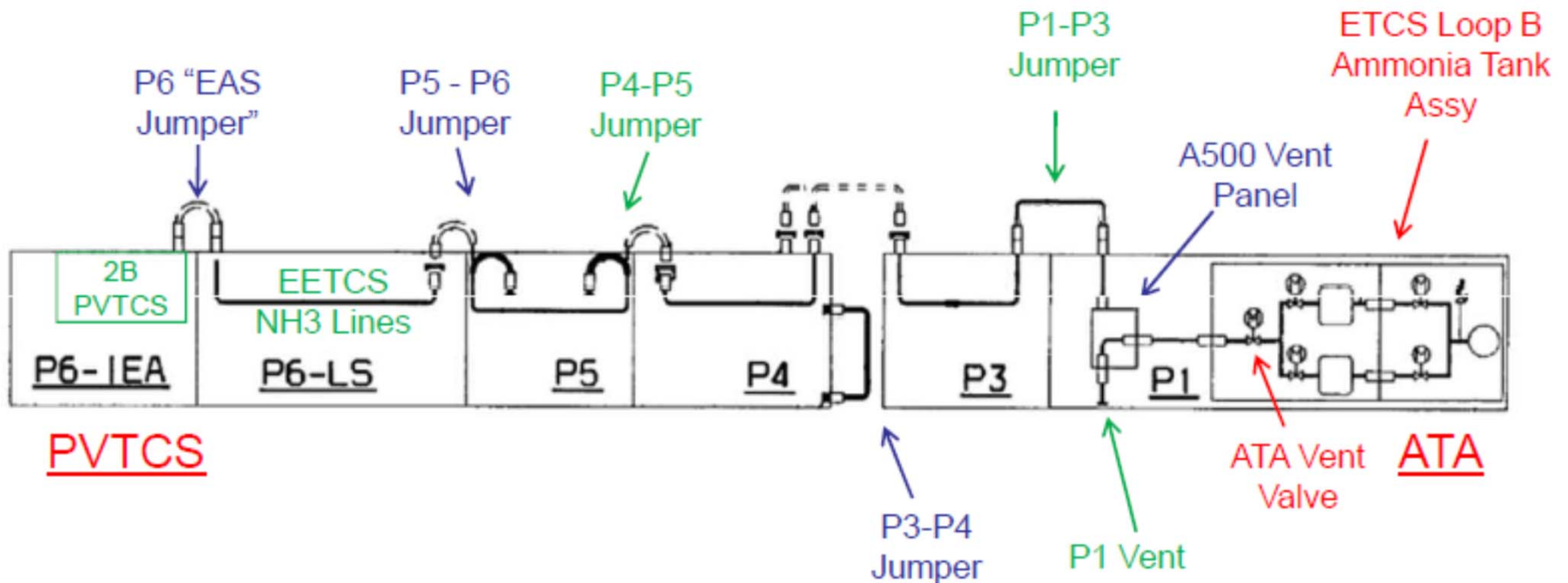
## The ISS Photovoltaic Thermal Control System Leak: An Operational History

- STS-134 EVA #2
  - May 22<sup>nd</sup> 2011
  - Goal:
    - Top off the 2B PVTCS by adding approximately 8lbm of NH<sub>3</sub>
  - Method:
    - Deliver a regulated ammonia charge from one of the central External Thermal Control System (ETCS) loops via a series of built-in conduits and EVA-installed jumpers from the P1 truss to the P6 truss
  - Time to Plan:
    - Approximately 20 months



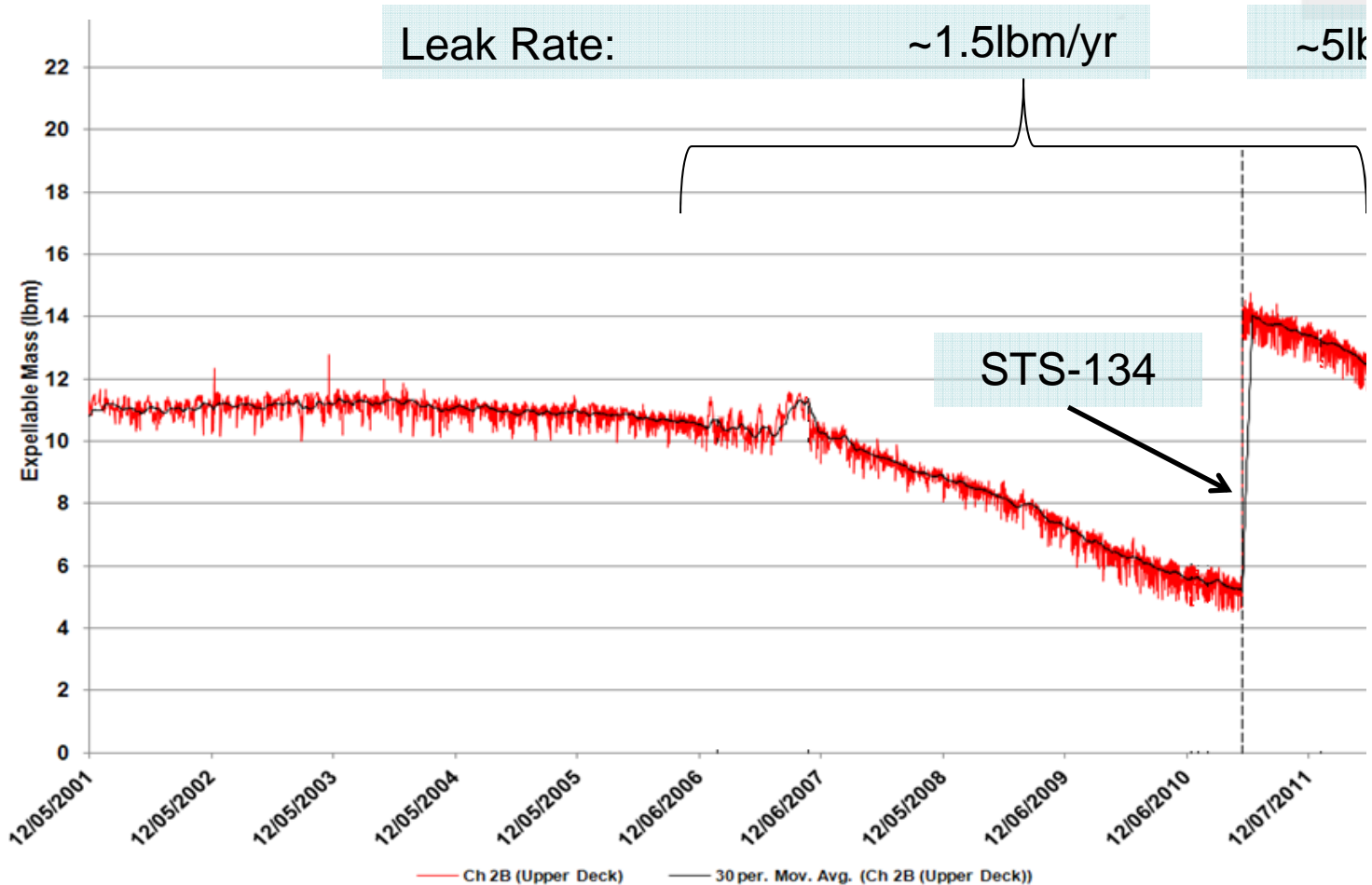
STS-134 Patch

# The ISS Photovoltaic Thermal Control System Leak: An Operational History



PVTCS Refill Capability

# The ISS Photovoltaic Thermal Control System Leak: An Operational History



2B PVTCS NH<sub>3</sub> Mass vs. Time (2001-2012)

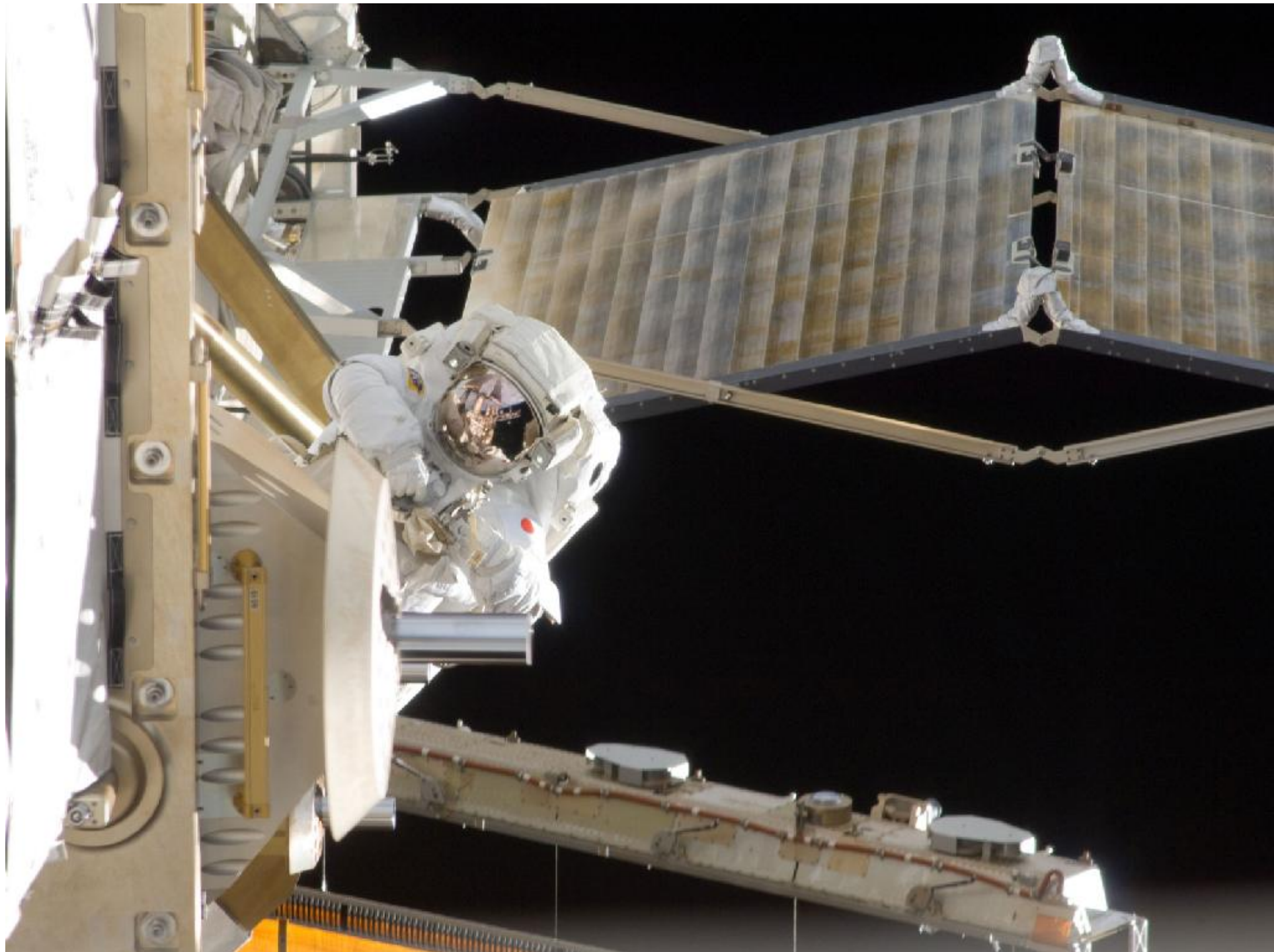
## The ISS Photovoltaic Thermal Control System Leak: An Operational History

- US Stage EVA #20
  - November 1<sup>st</sup> 2012
  - Goal:
    - Attempt to isolate accelerated PVTCS 2B Leak
  - Method:
    - Close valve to disconnect 2B PVTCS from radiator
    - Utilize fluid jumpers to reroute ammonia to an adjacent decommissioned ammonia loop with its own radiator
    - Deploy that radiator
  - Time to Plan:
    - Approximately 5 weeks



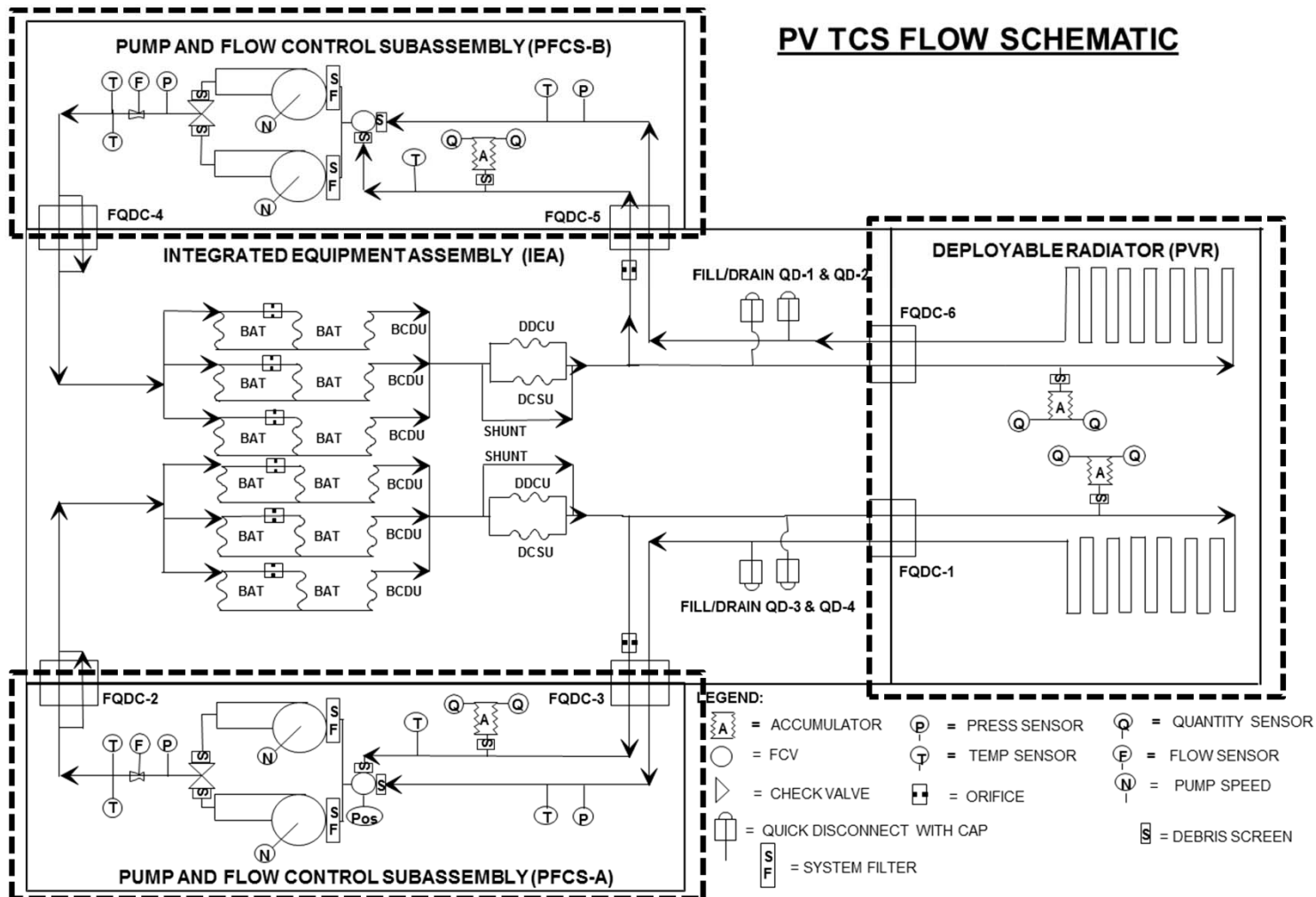
*Expedition 33 Patch*



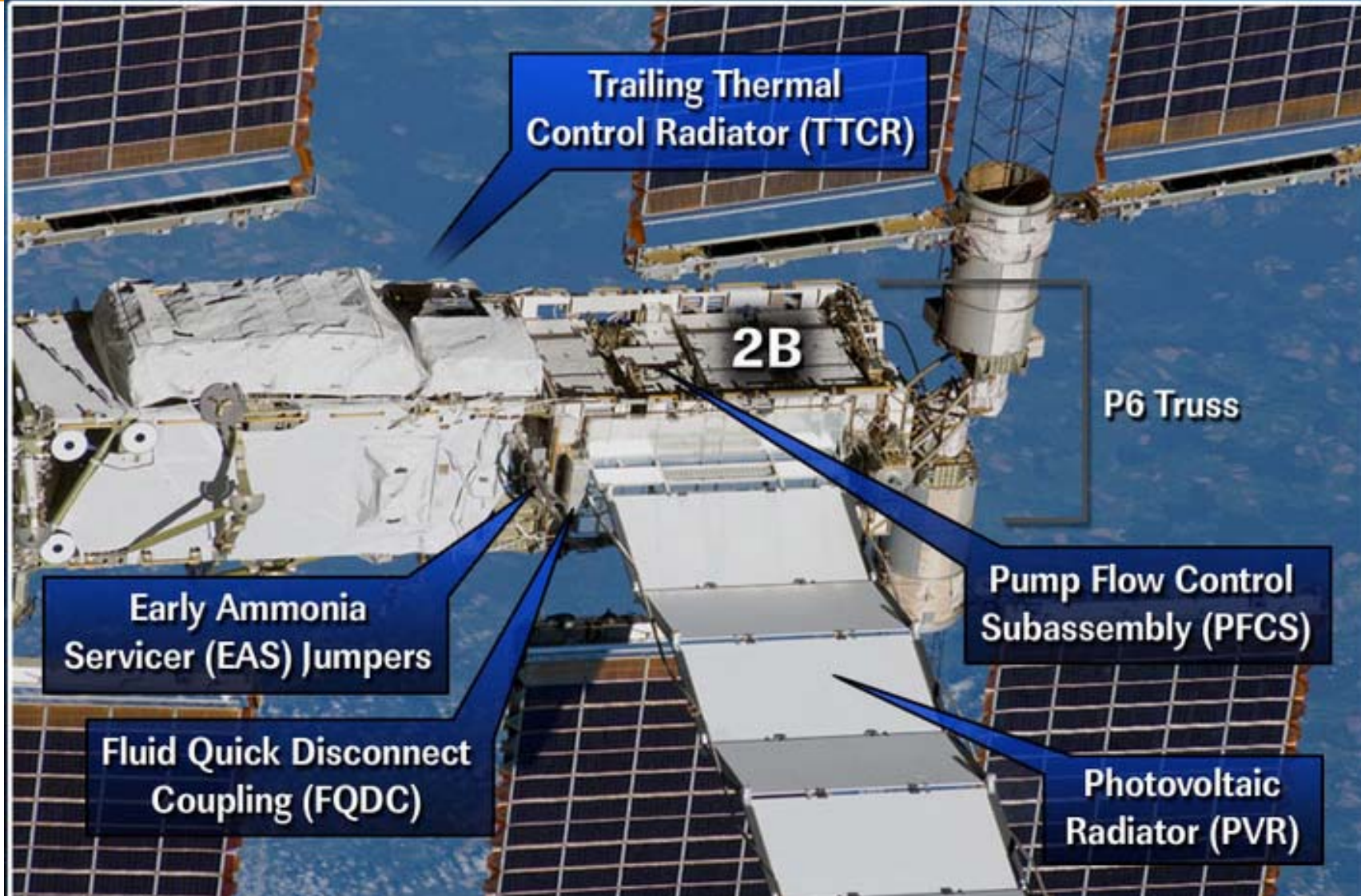




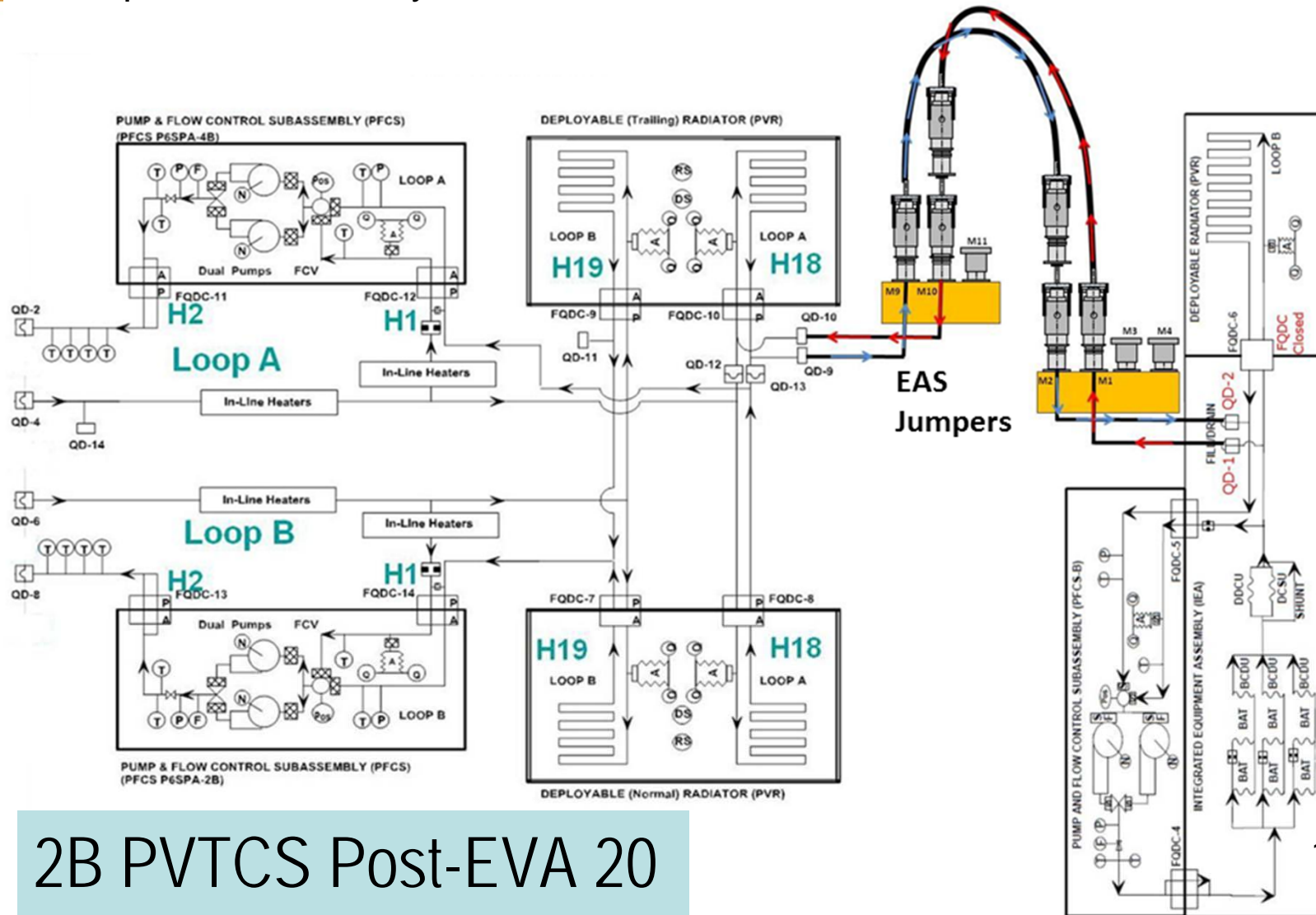
# The ISS Photovoltaic Thermal Control System Leak: An Operational History



## The ISS Photovoltaic Thermal Control System Leak: An Operational History



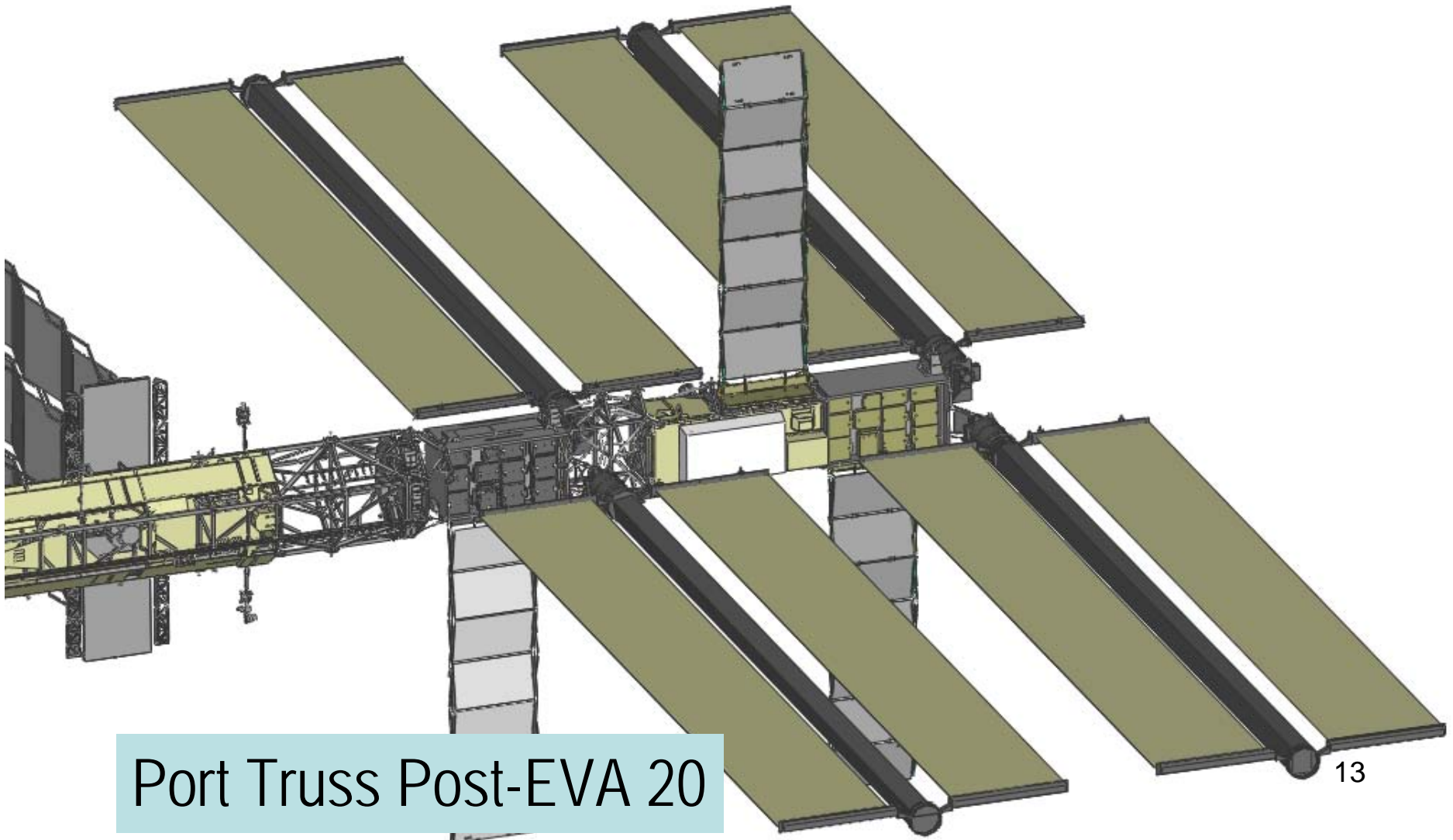
# The ISS Photovoltaic Thermal Control System Leak: An Operational History



2B PVTCS Post-EVA 20

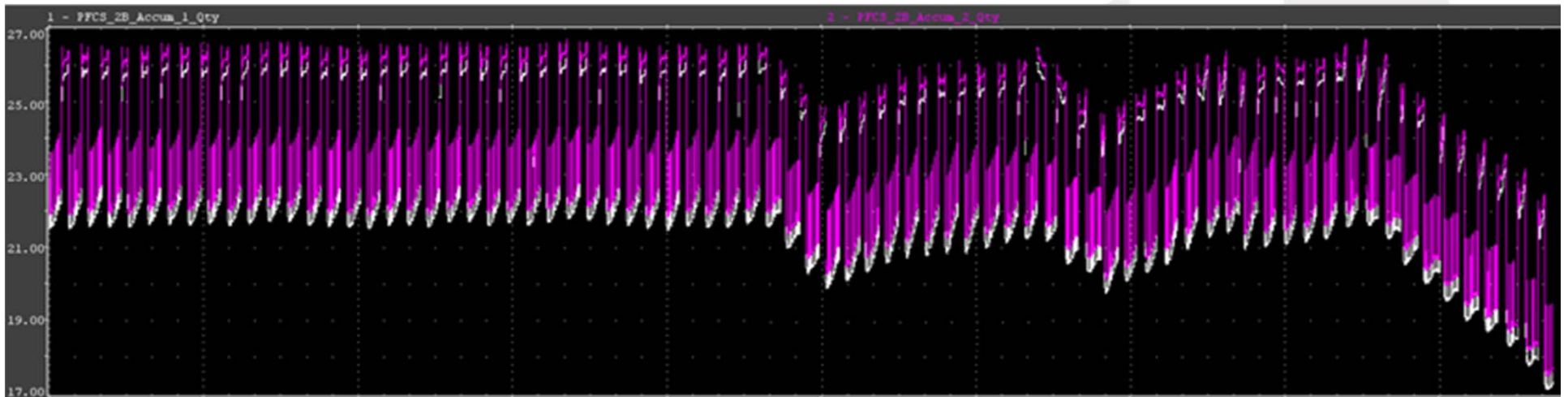


## The ISS Photovoltaic Thermal Control System Leak: An Operational History



Port Truss Post-EVA 20

# The ISS Photovoltaic Thermal Control System Leak: An Operational History



**A: Nominal quiescent system**  
Patterns form 'beats', with multiple nominal 1-2 orbit long dips and recoveries

**B: GMT 127 Solar array feathering for 33S thruster test**  
3 orbits downward trend then recovery, in family

**C: GMT 128 Solar array feathering for 51P reboost**  
3 orbits downward trend then recovery, in family

**D: GMT 129 2B PVTCS leak**

2B PVTCS NH<sub>3</sub> Qty vs. Time (~5 days in May 2013)

## The ISS Photovoltaic Thermal Control System Leak: An Operational History

- US Stage EVA #21
  - May 11<sup>th</sup> 2013
  - Goal:
    - Stop 5lbm/day visible overboard leak
  - Method:
    - Remove and replace 2B Pump Flow Control Subassembly (PFCS) with spare...
    - ...unless EVA crew determined it to be obvious that any other part of P6 truss was the culprit
  - Time to Plan:
    - Less than 48 hours

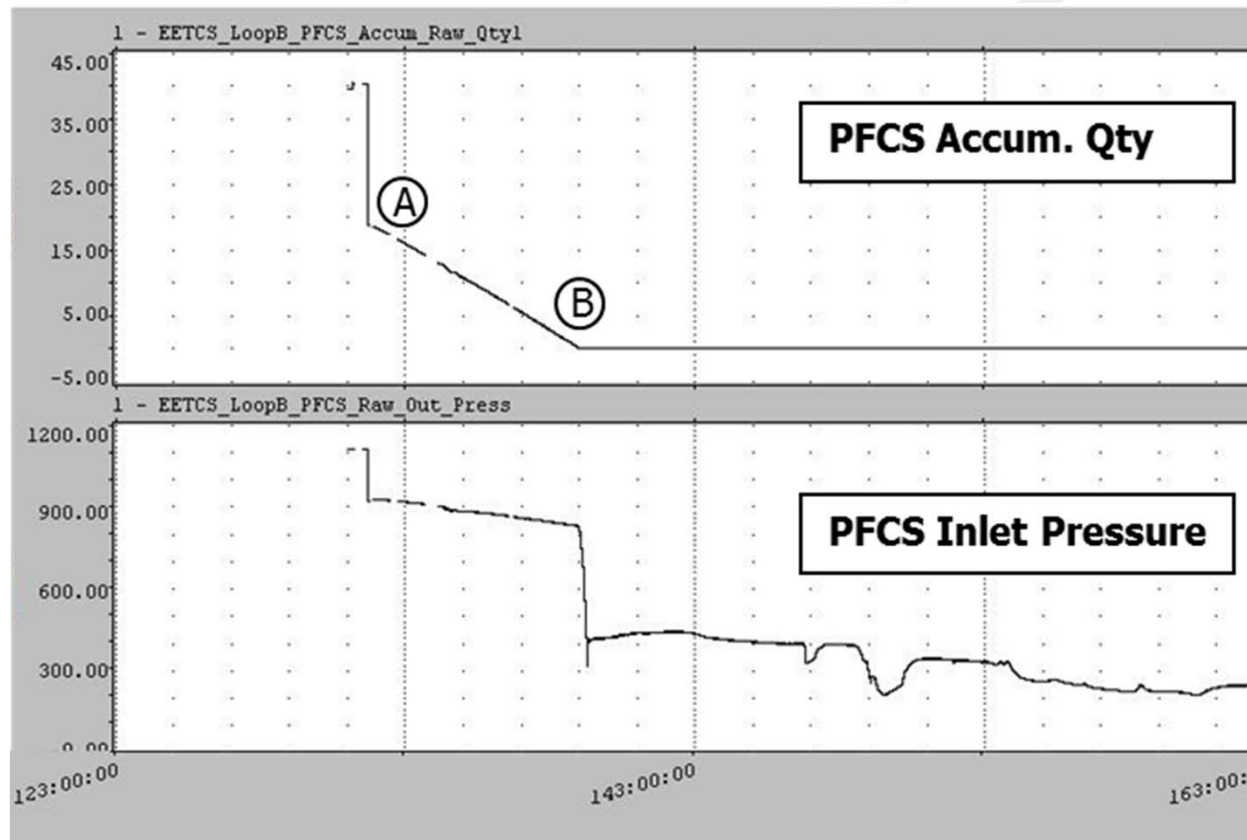


*Expedition 35 Patch*





## The ISS Photovoltaic Thermal Control System Leak: An Operational History



'Mr. Leaky' – PFCS S/N 0004 After EVA 21 Removal

## The ISS Photovoltaic Thermal Control System Leak: An Operational History

- Leak Status:
  - The 2B PVTCS leak was isolated to PFCS S/N 0004
  - Since May 2013, system mass has not appreciably changed
  - An EVA may occur as early as this summer to retract the TTCR and return 2B PVTCS to design configuration
- Conclusion:
  - ISS PVTCS leak mitigation capabilities were crucial to continuing successful operation
  - An operations mindset during the design process is a necessity



*The World's Forum for Aerospace Leadership*