A Review of Pump Package Assembly Anomalies and Demonstration to Gain Motor Controller Replacement Capability

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The International Space Station (ISS) generates heat within the US modules from systems used to operate the station, maintain crew health, and conduct science experiments in the orbiting laboratory. The Internal Thermal Control System (ITCS) collects this heat in water loops and transfers it to the external ammonia system for rejection to space. The ITCS uses six Pump Package Assemblies (PPA) as the motive force to circulate the water within the Lab, Node 2, and Node 3 (Node 1 is parasitic to the Lab and Node 3 ITCS loops). In the life of ISS, 3 PPAs have had to be replaced and 2 PPAs are currently showing signs of degradation. The first PPA to fail in 2003 was due to early coolant chemistry issues; the remaining pump failures and current pump degradations are determined to be related to the Pump/Fan Motor Controller (PFMC), with their individual signatures all being unique to this point. The PFMC of one of the failed PPAs was returned and testing confirmed its sub-components to be the root cause of the PPA failure. Due to the relative size and weight of the standalone PFMC in comparison to the integrated assembly, it is desired, from a launch and on-orbit stowage perspective, to replace the PFMC component of the degraded PPA instead of the entire PPA. The PPA was not designed for this capability, so on the ground demonstrations are planned using crew tools to show that the PFMC can be replaced on-orbit while maintaining full functionality. This paper will focus on the signatures of the two most recent PPA failures and the two PPAs showing signs of degradation, in addition to presenting the findings from the PFMC demonstration effort.

Acronyms and Nomenclature

amp	=	Ampere
ATCS	=	Active Thermal Control System
ATP	=	Acceptance Test Procedure
BIT	=	Built-in Test
C	=	Celsius
CCA	=	Circuit-Card Assembly
CDRA	=	Carbon Dioxide Removal Assembly
dP	=	Delta Pressure
EATCS	=	External Active Thermal Control System
EMI	=	Electromagnetic Interference
FOD	=	Foreign Object Debris
Hz	=	Hertz

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IFHX	=	Interface Heat Exchanger
ISS	=	International Space Station
ITCS	=	Internal Thermal Control System
JSC	=	Johnson Space Center
kg	=	Kilogram
kPa	=	Kilopascal
lbm	=	Pound-mass
LTL	=	Low Temperature Loop
MTL	=	Moderate Temperature Loop
OEM	=	Original Equipment Manufacturer
ORU	=	Orbital Replacement Unit
PFMC	=	Pump/Fan Motor Controller
PPA	=	Pump Package Assembly
psi	=	Pound per Square Inch
QD	=	Quick Disconnect
RPM	=	Revolutions per Minute
R&R	=	Removal and Replacement
SFCA	=	System Flow Control Assembly
TT&E	=	Test, Teardown, and Evaluation
USOS	=	US On-Orbit Segment

I. Introduction

THE International Space Station (ISS) must reject the heat it generates from the systems required to operate the station and the payloads on-board performing science. Heat generated within the Lab and three Node modules is collected by circulating water loops that make up the Internal Thermal Control System[1,2]. This system uses Pump Package Assemblies (PPA), Figure 1, to provide the motive force to circulate the water. PPAs are critical to the function of the ISS as a loss of the loop would cause systems to overheat and shut down. The heat is collected from the users using cold plates and heat exchangers. The heat is then transported to the Interface Heat Exchangers (IFHX) where it is rejected to the ammonia in the External Active Thermal Control System (EATCS) and rejected to space. Each module contains a Moderate Temperature Loop (MTL) and a Low Temperature Loop (LTL). There are six PPAs installed in the Internal Thermal Control System (ITCS), with one assigned to each loop in the Lab, Node 2, and Node 3 module to provide fault tolerance to each module. Node 1 does not contain any PPAs as its heat load is managed by the Lab and Node 3 loops. In Lab and Node 3, these two loops can be combined so that a single PPA can operate both loops. This is how Lab is nominally operated.

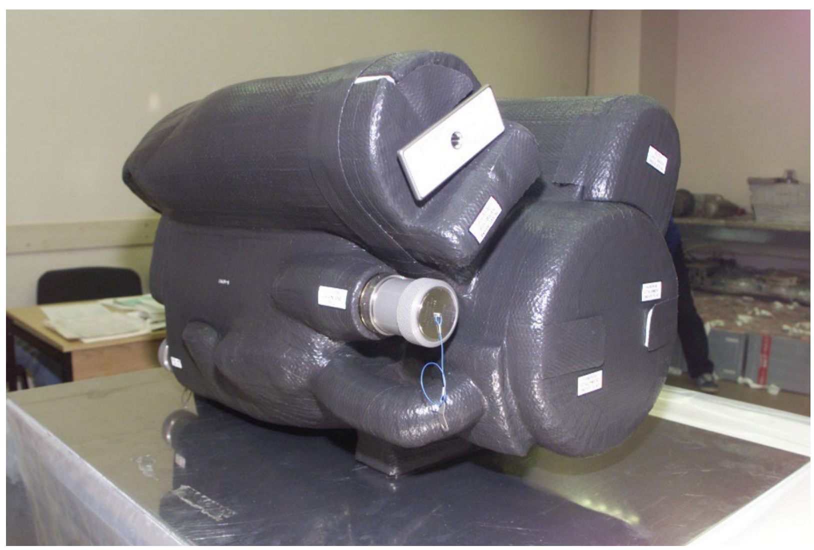

Figure 1: PPA

Over the 25-year life of ISS, there have been three PPA failures that have required replacement and two are currently exhibiting signs of degradation. The first PPA failure was due to coolant chemistry issues which have since been resolved. The other two failures and two PPAs degrading are believed to be caused by the Pump/Fan Motor Controller (PFMC), which is the internal motor controller that is responsible for speed control and fault monitoring seen in Figure 2. The PFMC from one PPA was returned to ground and sent to Honeywell, PPA Original Equipment Manufacturer (OEM), for Test, Teardown, and Evaluation (TT&E). The PFMC was not designed to be replaceable on the PPA, so ISS crew had to destructively remove the PFMC from the PPA without damaging the PFMC. The TT&E

confirmed the PFMC to be the root cause of that PPA failure. This testing along with the fault assessment of each PPA points to the PFMC as the most likely cause of failure.

Identifying whether a PFMC is the root cause while the PPA is on-orbit is not straight forward. The PFMC does have some Built-in Tests (BIT) which periodically monitor the health status of the PFMC, but there have been multiple failures where no BIT flags were triggered. Telemetry from the PPAs is trended to capture any changes in performance over the long term. This can capture any degradation in the pump's performance or clogging of the filter or gas trap. Most PPA telemetry is relayed to the ground at a full data rate of one Hertz (Hz) which cannot be updated. This data rate is sufficient for the long-term trending, but not when there are highly dynamic transients. The PFMC control cycle is much faster at 100 Hz which means, in some cases, it is not possible for telemetry to fully capture the event. In most cases, the PPA either recovers by itself or a restart returns it to nominal operation, but at a reduced speed. Signs like these point to the PFMC as the root cause. Being able to reliably replace the PFMC on-orbit can save up-mass and on-orbit storage while preserving the ability to return an ITCS loop to operation without a full PPA Removal and Replacement (R&R). The PPA requires ground servicing and being a large piece of hardware, requires a large allocation of launch mass and on-orbit stowage. The PFMC is much smaller and does not require ground servicing. In the event of a PPA failure that is recognized as a PFMC failure, the PFMC could be replaced, returning the PPA to full function.

Figure 2: PFMC

II. PPA Failures

The PPA is an Orbital Replacement Unit (ORU) that was designed to be replaced by crew into all six of the US On-Orbit Segment (USOS) ITCS loops. It consists of a pump, inlet and outlet Quick Disconnects (QDs), temperature, inlet pressure, delta pressure (dP), and flow sensors, an accumulator with a quantity sensor and nitrogen connection, fill port, and electrical connectors for power and data. The PPA also contains a filter and gas trap that are designed to be removed by crew as independent ORUs. Figure 3 references a functional diagram of the PPA. The inlet and outlet QDs connect the PPA to the rest of the ITCS. The filter captures particulates, and the gas trap removes free air from the loop to protect the PPA from clogging, cavitation, and air locking the impellor in the pump. The dP sensors monitor the health of the filter and gas trap. The accumulator holds back pressure on the PPA and can replace coolant lost in the loop. It is pressurized by the ISS nitrogen system and has a fill port for crew to refill the accumulator. The quantity and inlet pressure sensor monitor the back pressure on the pump and can be used to monitor system wide leakage. The dP sensor on the pump, pump speed sensor and outlet flow meter provide indications on the performance of the pump. The PFMC controls the pump speed and monitors pump health. Flight computers command the pump speed and the PFMC uses a closed-loop control to maintain that speed. The sensors are read by flight computers and relayed to the ground as telemetry.

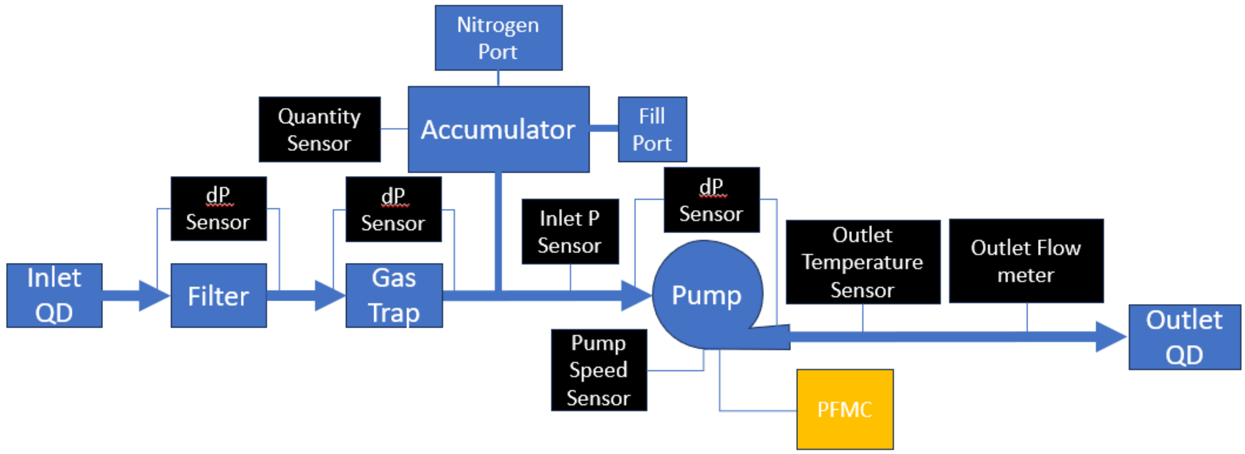

Figure 3: PPA Functional Diagram

Prior to 2015, the six ISS PPAs experienced no failures or anomalies in their pumping capability except for the PPA failure in 2003 that was due to coolant chemistry. Since 2015, four different PPAs have experienced sporadic anomalies. The signature of each anomaly is unique but does not impact the pump's performance in the loop when the PPA is operating nominally. To assess each anomaly, a fault tree was created (Figure 4). This fault tree was used to determine possible troubleshooting steps and to help generate a root/probable cause. None of the anomalies forced an immediate R&R, so long-term trending of the failure was possible. Given resource constraints of purchasing new PPAs and launching additional PPAs, the decision was made to run all the pumps to failure, or until the anomalies became too cumbersome to manage. With the criticality of the PPA, sometimes the next worst failure would also factor into when the decision to perform a R&R was made. The following sections will discuss the four anomalies and the results of the subsequent investigations.

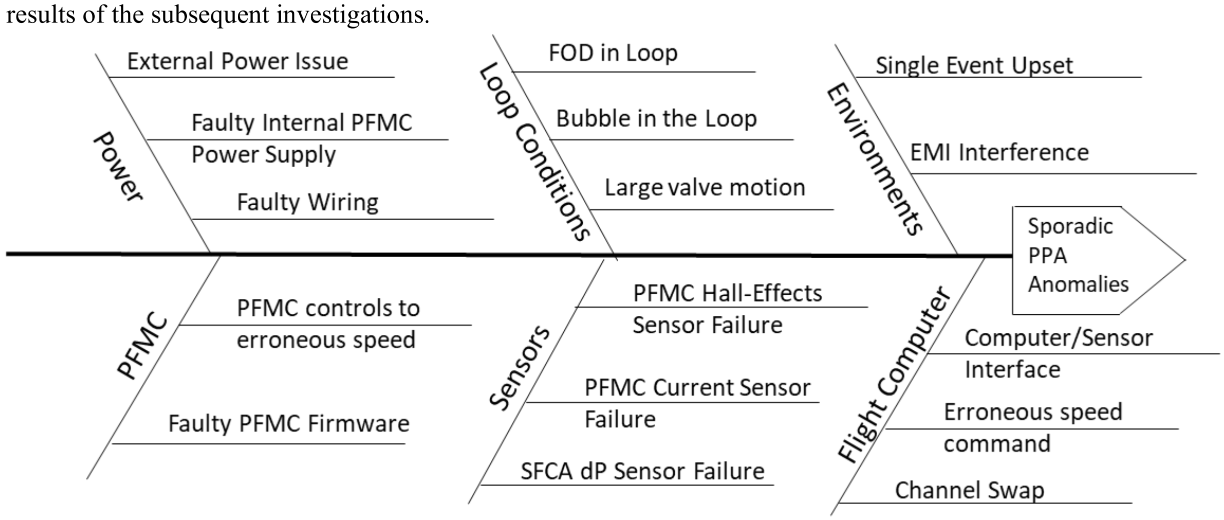

Figure 4: PPA Anomaly Fault Tree

A. Node 3 LTL PPA

In May of 2017, Node 3 was transitioned to Single LTL for maintenance on an unrelated avionics box. In single loop mode, both the MTL and LTL are cooled by a single PPA, with Single LTL having the LTL PPA as the actively spinning pump. To achieve adequate cooling to both the LTL and MTL, the pump speed of the PPA is increased. Node 3 operated in this mode for five days and throughout the five days, the pump experienced almost 100 anomalies. These anomalies were characterized by rapid (<one second) drops in PPA speed. After each anomaly, the PPA returned to nominal operation. The magnitude and frequency of the transients were inconsistent. The anomaly was present in pump speed, current, flowrate and Gas Trap and Filter dP. The transient was also seen on the System Flow Control Assembly (SFCA) dP. Figure 5 shows this phenomenon. The SFCA is a valve that maintains the dP across the ITCS

users so that they receive a constant flow. This shows it was a real, hydraulic event and not a data issue in the PPA. The pump spun down and back up over the course of two seconds with the largest speed change being from 18.9K to 12.3K RPM. These anomalies never triggered a fault that caused any system response because the speed returned to nominal before three seconds.

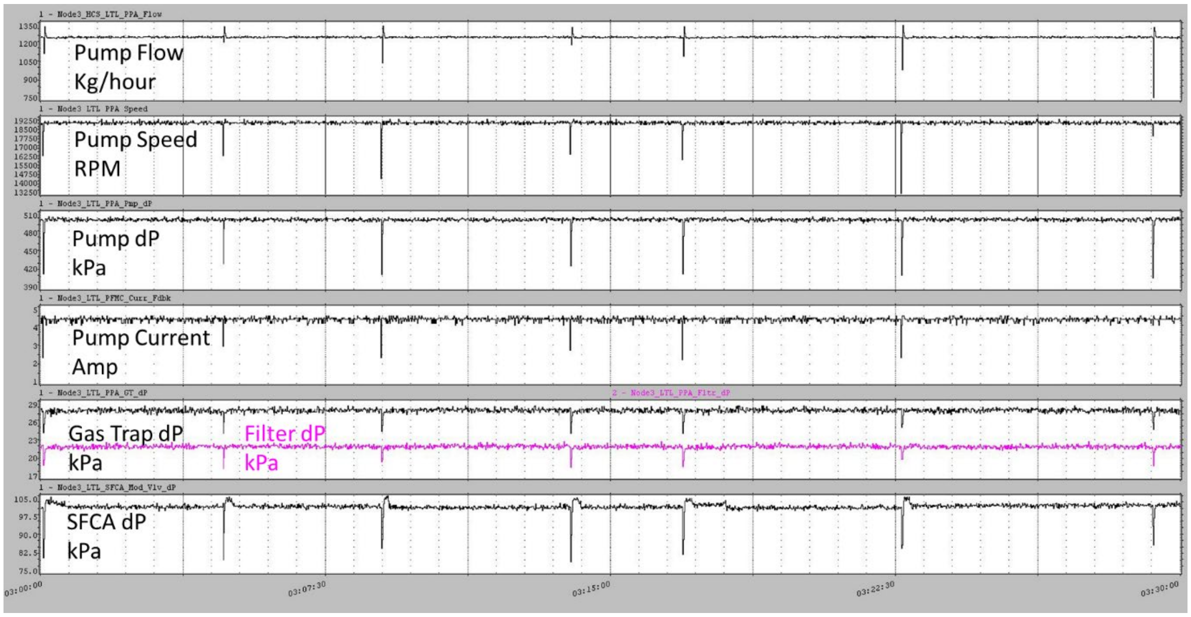

Figure 5: Node 3 LTL PPA Anomalies (30 Minutes of Data)

These anomalies never occurred in Dual mode. In Dual mode, both PPAs are pumping their own loop (MTL and LTL). The Node 3 LTL PPA is also operating at a lower speed (10.8k RPM). After the anomalies were seen in May 2017, data from previous instances when Node 3 was in Single LTL were examined. It showed this anomaly occurred in 2015 (previous instance Node 3 was in Single LTL) at a rate of nine events over three days. Node 3 was in Single LTL six times between 2012 and 2015 and showed no anomalies. This anomaly was also not present when Node 3 was in Single MTL. Due to the architecture of Node 3, loss of the Node 3 LTL PPA did not result in any loss of function in Node 3. For Node 3, Dual mode is the nominal operating configuration, so the LTL PPA is rarely operated at the higher speed.

Based on the telemetry, a few branches of the fault tree could be ruled out. Power to the PPA was nominal and no commands or channel swaps occurred in the ISS software. Single Event Upsets and Electromagnetic Interference (EMI) was ruled out by assessing known sources of radiation and EMI. The SFCA dP sensor and large valve motion was ruled out because telemetry showed the valves responded to the pump speed changes. Foreign Object Debris (FOD) and bubbles in the loop were also ruled out due to the low filter and gas trap dP. This indicates a clean filter and no gas in the gas trap. This left most of the possible causes internal to the PFMC. The only cause not internal to the PFMC was a Hall-Effect Sensor failure as this sensor is external to the PFMC.

With the increase in frequency from 2015 to 2017, it appeared that the PPA was degrading. To monitor the degradation, Node 3 was transition to Single LTL every three to four months for a three-day period. Every three-day period showed an increase in frequency. Even at the increased frequency, nominal cooling was being provided to all the Node 3 ITCS users because the transients were so fast, cooling was never truly lost. Of primary concern with the increase in frequency is the increased odds that multiple events could stack together trigger a fault response. The PFMC will trigger a fault if the speed drops below 17.6k RPM for three consecutive seconds. In March of 2018, during the last three-day Single LTL period, two events happened 1 second apart which nearly triggered the fault. While this didn't constitute a failure, trust in the PPA's ability to maintain cooling was lost. Single LTL would be required if there was an issue with the MTL PPA, either with the PPA itself or the power and software that operates the PPA. If Node 3 were forced to operate in Single LTL, loss of the LTL PPA due to this anomaly would result in loss of cooling to Node 3. The decision was made in April 2018 to R&R the PPA to return full fault tolerance to Node 3. Due to return mass constraints, the failed PPA was not returned for TT&E. The new LTL PPA in Node 3 has continued to operate nominally, even in Single LTL mode, since being replaced.

B. Node 2 MTL PPA

In October of 2019, the Node 2 MTL PPA experienced two anomalies over the course of two days. These anomalies again were highly dynamic but seemed to indicate a speed increase over the course of one second. The speed increase was seen in pump speed, flowrate, and pump, filter, and gas trap dP. It was also seen again in the SFCA dP which points to a true hydraulic event. In this case, faults were detected and the PPA either shut itself down or flight software commanded a reduction in the PPA speed to safe the system. Node 2 does not have single loop capability so loss of the PPA means loss of the loop. Fortunately, ground teams were quickly able to restart the PPA and return the loop to nominal function. The PPA also responded nominally to all ground commands. Two different fault responses were triggered by these anomalies. The first restarted the pump, although no fault flag was triggered. The second responded to the increase in SFCA dP. Due to the sensitive nature of the dP sensor in the SFCA, flight software is designed to reduce the PPA to a safe speed if the SFCA dP is too high.

This anomaly did not recur for almost six months. In March of 2020, there was a speed spike, smaller in magnitude, that did not trigger a fault. It was only identified by data review. The next anomaly occurred in April 2020 with a different signature. This signature showed speed increased to the maximum speed the PPA can achieve (20k RPM) and lost connection to the flight computers. Interestingly, the other telemetry showed a speed decrease but still no fault triggered. The speed telemetry from the PPA comes to the ground in three bytes. The three bytes recorded speed in the millions of RPM, or off-scale high. It was determined this was the cause of the loss of connection to the flight computers. The PPA sent a speed over the limit of what the computer was expecting, and this failed the computer causing a channel swap. This was quickly remedied with a software update. Separately, this also caused the PPA to exceed the 22K overspeed limit which forces an immediate shutdown. It should be noted that this fault does have a fault flag, but the flag only triggered during a few instances of this anomaly. This is due to the flight computer issues and the fact that the data rate for the fault flag is only 0.1 Hz. The fault causes the PPA to restart and if the restart was successful, which it always was, would clear the fault. This masked the flag in all but a handful of instances.

Throughout April and into May, the rate of anomalies rapidly increased. The different signatures continued to manifest with no clear pattern. To get more data, the pump speed was increased to 13K RPM. This resulted in a noticeable increase in the frequency of anomalies even after the pump speed was lowered to the nominal 9.4K RPM. The anomalies were occurring multiple times a day which became cumbersome for flight controllers to manage. The decision was made to R&R the PPA at the end of May and the new PPA has operated nominally ever since.

It's difficult to believe a pump that was designed for a maximum speed of 20K RPM could achieve speeds 1000 times greater, even for a moment. Based on other telemetry, it’s clear the speed did in fact increase some amount. The fault tree for this anomaly is similar to the one for the Node 3 LTL PPA. All power and data (after the software was updated) appear nominal as does Single Event Upsets and EMI. FOD in the loop or large valve motion could not have caused these large speed increases. It’s possible an air bubble entered the impellor causing the overspeed, but this would have reduced the flowrate, not increase it like was seen during these anomalies. The PFMC speed control runs on a 100 Hz cycle so it’s possible an erroneous reading from the hall-effect sensor could have caused the overspeed. Finally, the root cause could have been within the PFMC.

1. PFMC Removal and TT&E

There was a strong desire to return the PPA for TT&E to determine the root cause of the failure. With the previous Node 3 LTL PPA failure, there was also a concern that the aging PPA fleet would start failing. Due to size constraints and down mass priorities, returning the entire PPA was not feasible. Given the failure had been narrowed down to either the PFMC or hall-effect sensor, the decision was made to return only the PFMC and dispose of the rest of the PPA. If the PFMC is tested and shown to be without defect, then the hall-effect sensor was the likely root cause. As the PFMC was not designed to be removed, new procedures were developed to remove the PFMC. Figure 6 outlines the process for removal. With the rest of the PPA being disposed of, crew did not have to carefully remove the insulation. This saved time and effort but left much of the insulation in pieces. If crew were to replace the PFMC, crew would have to reinstall the insulation so that condensation would still be prevented, which could be difficult if not removed carefully. Once the PFMC was removed, it was returned to the ground and sent to Honeywell for testing.

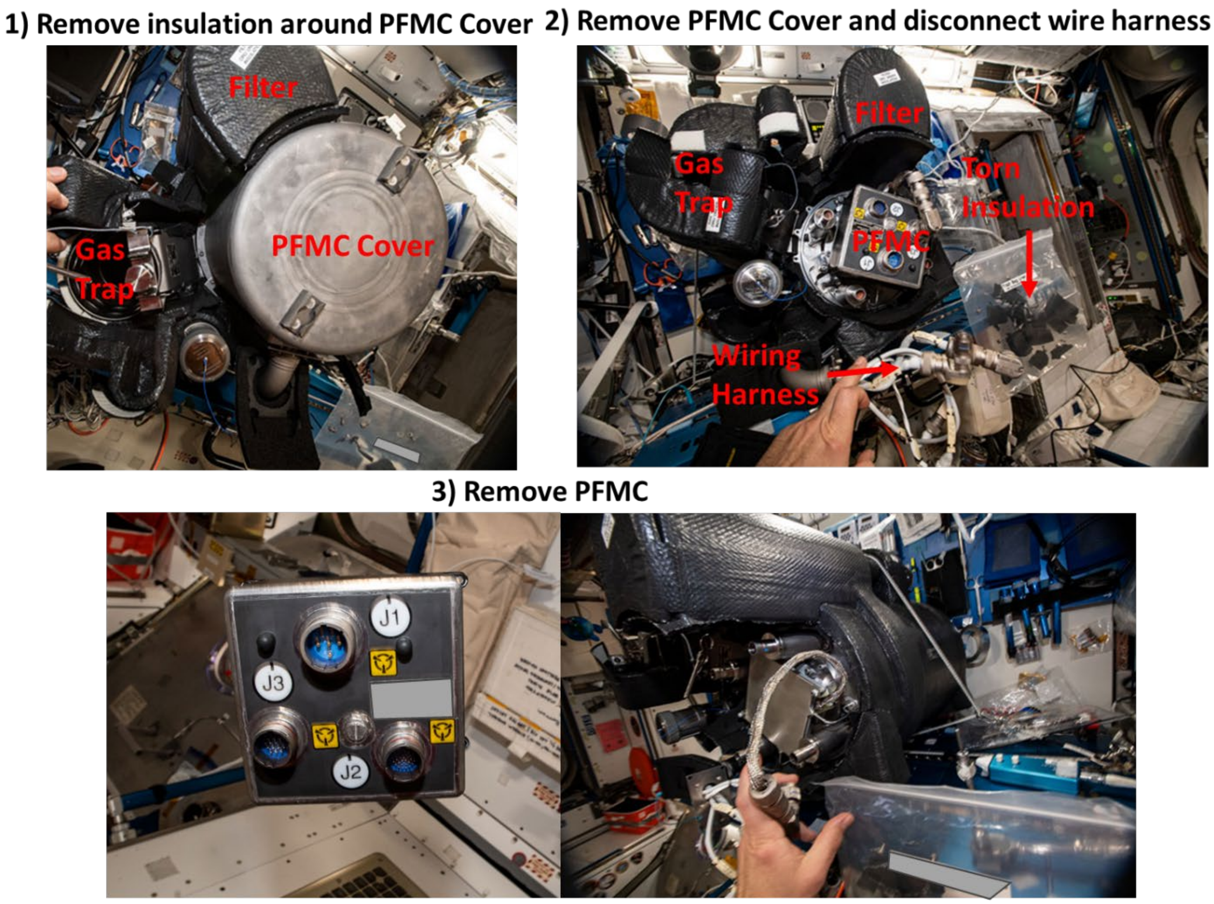

Figure 6: On-Orbit PFMC Removal

Honeywell began the TT&E by checking the resistance across the electrical connector pins and chassis which all showed nominal. A functional test was then performed on the PFMC without an anomaly. The data was compared to the pre-flight values which were in family. The functional test, which is a portion of the Acceptance Test Procedure (ATP), only operated the PFMC at maximum speed for 30 seconds. The test was re-run at the nominal speed of 9.4K for four hours. During the test, two events where speed sharply increased and returned to nominal speed over the course of one second occurred. This and subsequent tests showed the returned PFMC anomaly rate was about eight per 24 hours of runtime compared to the average three per day on-orbit when the PPA was removed.

An oscilloscope was used to measure current from the PFMC and captured dozens of current spikes where current doubled for 0.3-0.4 seconds. This is why on-orbit data never captured more than a data point of the anomaly. The PFMC was also tested at 20K RPM and showed a different signature where current spiked down for a shorter period (0.03-0.04 seconds). The frequency was also higher. The tests were repeated while capturing the output phase-voltage and input hall-effect sensor voltage with results showing the root cause was likely in the inverter or microprocessor Circuit Card Assembly (CCA). To determine which CCA was at fault, the PFMC cover had to be removed to test the internal components. These tests showed the microprocessor CCA was sending incorrect current commands. It was also determined this was due to faulty hall-effect speed signals. Signals coming into the microprocessor were being corrupted by the Schmitt Trigger. The Schmitt Trigger is a microcircuit meant to clean up the analog hall-effect sensor signal and send it to the microcontroller to calculate speed. The Schmitt Trigger would glitch and send an extra signal that the microprocessor would interpret as a high-speed value. This would cause the microprocessor to react incorrectly yielding anomalous behavior. With the root cause determined, the PFMC could have been repaired. Due to cost, and the ample ground spares, it was decided to shelve the PFMC and not proceed with the repair.

C. Node 2 LTL PPA

In July of 2022, the Node 2 LTL PPA experienced an operational anomaly leading to a loop failure. The fault detection software proceeded into the retry algorithm, which recovered the PPA successfully. Unlike the anomaly on its sister unit on the Node 2 MTL, telemetry did not show any mechanical or hydraulic response prior to failure. The operational mode transitioned into a diagnostic state, stopping the pump, before the PFMC communicated through the recovery software to return to its operational state at a reduced pump speed. Composite data related to the PPA portrayed nominal health preceding and proceeding the recovery of the loop. Flight controllers returned the pump to nominal speed following the automatic recovery. Figure 7 shows the filter, gas trap, and pump dP, SFCA response, and pump speed exhibited behavior requisite to a pump restart and speed increase during the anomaly response.

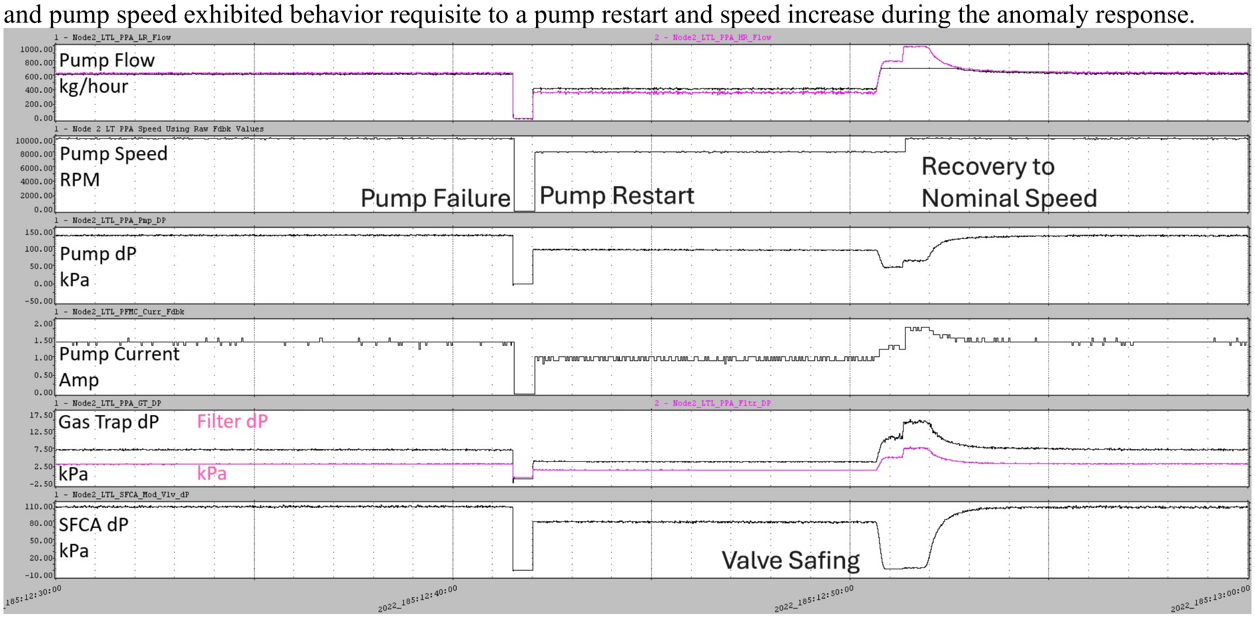

Figure 7: Node 2 LTL PPA Anomaly (Initial Occurrence)

After this initial failure, the failure did not recur until September of 2023. With each recurrence that followed, PFMC fault data, PPA diagnostics, and software connections were analyzed to determine an approximate cause. The signature of each recurrence established a running pattern, with the operational mode transitioning, leading to a PFMC fault and subsequent recovery conducted by the on-orbit software programming. No PFMC fault flag was triggered. ISS flight path data was also analyzed to determine whether radiation may be a contributing factor. A common orbital location for failure was not delineated.

To date, the anomaly's frequency has increased, but the requisite signature has not deviated from the original failure event. Ground operations have optimized recovery time to ensure the loop does not operate at reduced cooling for long periods of time. A decision to R&R the Node 2 LTL PPA has not been determined at this time given the known signature of the failure and ease of recovery relative to available resources, though the frequency is slowly increasing. Once the frequency becomes difficult for flight controllers to manage, the PPA R&R will be conducted to return Node 2 LTL to nominal operation.

D. Node 3 MTL PPA

In August of 2024, the Node 3 MTL PPA exhibited an increasing temperature within the PFMC despite no change in commanded loop setpoint or pump speed. In the hours preceding the loop failure event, the PPA, gas trap, and filter dP, pump speed feedback, current, and voltage did not exhibit anomalous behavior. Following the initial spike to just below the overtemperature fault limit, the temperature regressed before increasing back above the 100 Celsius (C) fault limit (Figure 8). Upon reaching the fault threshold, the MTL PPA attempted to recover via flight software before being deemed failed. Node 3 has single loop capability, so flight software combined the LTL and MTL and used the LTL PPA to recover the Node 3 ITCS. The overtemperature fault BIT within the hardware that tripped did not fall below the 100 C limit even after the PPA was restarted.

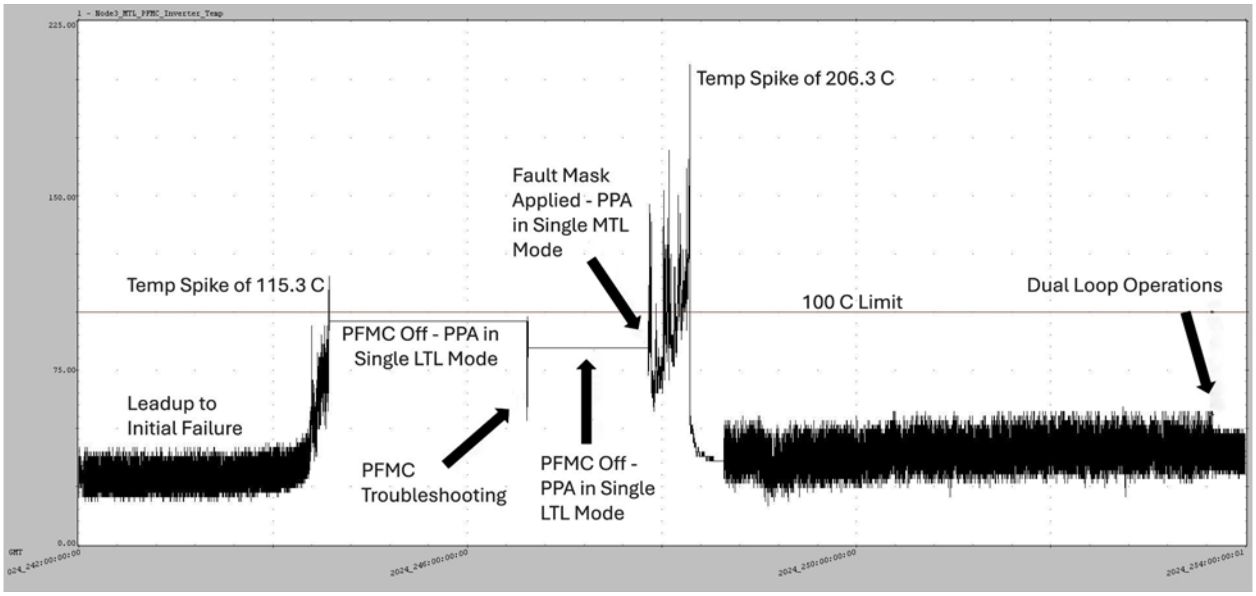

Figure 8: Node 3 MTL PFMC Inverter Temperature Data

Due to the fault tolerance provided by single loop operations, the investigation into the Node 3 MTL PPA failure could proceed without having to R&R the PPA to recover the loop. The overtemperature fault reading uses a transducer temperature sensor to convert voltage into a temperature reading, with device error increasing after it surpasses its upper limit due to potential sensor damage. This sensor is a part of the Inverter CCA, with no availability for replacement on orbit. To gather additional data on whether the temperature sensor could be trusted, the PPA was restarted 48 hours after the failure which allowed the temperature to cool off (Figure 9). While the PFMC temperature data originally showed a decreased PFMC temperature, the sensor reported increasing temperatures once the PPA was turned back on. The test was aborted before the 100 C limit was reached and Node 3 was returned to Single LTL. The methodology for conducting the operational test was due to this signature not being a first occurrence.

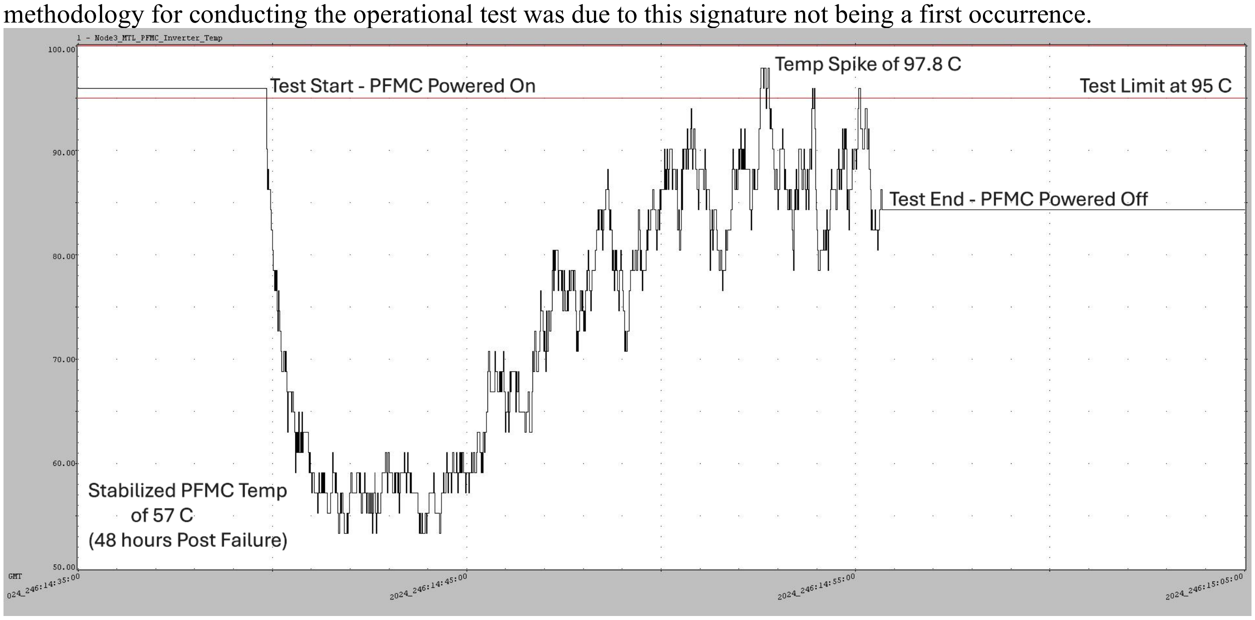

Figure 9: PFMC Inverter Temperature During Troubleshooting

This anomaly had been previously seen on the Carbon Dioxide Removal Assembly (CDRA) which also uses a PFMC. During the timeframe of the CDRA anomaly, the temperature sensor was determined to be erratic following data monitoring and discussions with the OEM, Honeywell. To not cause operational contingencies after determining the erratic nature of the transducer sensor, a fault mask was put in place over the BIT for the overtemperature fault. In addition to the overtemperature fault, there is a secondary sensor within the inverter CCA to ensure the hardware safes itself should the PFMC be reading temperatures more than the higher inverter shutdown fault limit (150 C). This inverter temperature operates without live data available, unlike the transducer temperature sensor.

To test the effectiveness of the fault mask, the Node 3 MTL PPA was operated in Single MT for a period of five days. After the restart of the PPA, the temperature data remained erroneous before achieving its highest reading and dropping back to within a few degrees of the original temperature reading from before the loop failure. After the operational test in Single MT was completed, the loop mode was shifted back to its nominal operational mode of Dual and the Node 3 MTL PPA is considered a degraded yet operational hardware. Since September of 2024, the data relayed from the transducer temperature sensor has varied from nominal data to a bias high, with intermittent temperature spikes up to 223.7 C. In comparison to the Node 3 CDRA PFMC signature, the Node 3 MTL PPA PFMC has exhibited more intermittent spike events while exhibiting a similar erratic behavior in temperature over time. The data from the transducer has trended towards a higher bias with time. Prior to failure, the Node 3 CDRA PFMC exhibited off-scale high temperatures until the point of a loss of communication. With only one available reference point, the Node 3 MTL PFMC temperature will continue to be monitored, while being prepared for an R&R should the hardware hard fail rather than continue to operate.

III. PFMC R&R Feasibility

The PFMC was not designed to be removed from the PPA so determining the feasibility of R&R was required before a standalone PFMC could be launched. Crew was able to remove the PFMC on-orbit so that gave good confidence it was physically possible. Of primary concern was showing the insulation could be reinstalled by the crew. The LTL PPAs operate below the dew point so if the insulation fails, condensation could form and cause microbial growth, corrosion, or electrical shorts. The PPA is covered in insulation to preclude condensation with openings only for connectors, the filter, and gas trap. To access the PFMC, the insulation will have to be removed along with a metal cover. Once the cover is removed, the connectors that connect the PFMC to the PPA can be accessed and removed. Once removed, the PFMC can be removed from the PPA. This operation was performed on-orbit by crew as a feasibility exercise and so that the PFMC could be returned to verify it was the root cause. This showed a PFMC failure could be identified on-orbit so the option of repairing the PPA was assessed. Of critical concern was crew's ability to reinstall the insulation and reassemble the PPA using only tools available on orbit. To verify this, an effort at Honeywell took place to take a flight PPA, remove its PFMC, and complete an acceptance test of the PFMC confirm it was not damaged. The PFMC was then replaced into the PPA and insulation was reinstalled using techniques available to crew. The PPA underwent a condensation test and modified acceptance test which showed the PPA operated as expected. This gives confidence that crew could reliably replace a PFMC on-orbit and the option to fly PFMC units instead of a whole PPA. The ATCS and Flight Controller Maintenance teams, working with Honeywell, documented this exercise which provided critical data for procedure development.

While working through the feasibility for an on-orbit R&R, testing different tooling combinations and routing of insulation incisions helped to influence future operations to find the most effective removal path for the insulation. Due to the hardware's temperature distributions, the thickness of insulation covering the PPA varies. The range of motion afforded by available crew instruments for cutting insulation within the activity can impact crew stamina from the repetitive actions of cutting through the insulation. From an efficiency standpoint and to preserve tool effectiveness, this led to discussions balancing generation of debris while cutting the insulation, navigating areas of increased thickness, and limiting any extraneous cuts for the purpose of minimizing fatigue. As noted in Figure 10, the focus path determined within the demonstration maximized thinner insulation areas from a fatigue standpoint. An additional objective was to be able to proceed forward with as few independent pieces of insulation as possible. During the feasibility demonstration at Honeywell, the methodology followed led to two total pieces of insulation removed: one piece fitting around the PFMC cover and the gas trap, fill drain port and filter mounts and one smaller fitted piece around the wiring harness cover.

Figure 10: PPA Insulation Removal (Top), PFMC Removal (Bottom Left), and PPA Repaired (Bottom Right)

As previously described, the feasibility of a PFMC R&R revolutionizes what had been originally considered to be a non-replaceable piece of hardware. Through the efforts of the PFMC being documented as an independent ORU similar to the gas trap and fine filter assemblies, the PPA can now be sustained for expanded mission performance should the anomaly be isolated to the PFMC and not the PPA's hydraulic mechanisms. In the upcoming era of long duration spaceflight missions, hardware which can be recovered through the anomaly-dependent replacement of piece part ORUs rather than the full hardware will help to balance what has been one of the logistical constraints of spaceflight cargo planning.

IV. Conclusion

The pump is a critical component of any active thermal control system and must remain operational to ensure heat can be collected and transported out of the vehicle. For the ISS ITCS, the motor controllers within the PPAs have proven to be the life-limiting factor. Throughout the investigations, the analyzed hardware has been reviewed through the lens of operational life and expected wear of its components. PPAs were designed for a ten-year lifespan. The Node 3 LTL PPA operated for eight years, while the Node 2 MTL PPA lasted twelve and a half years before failure. Currently, the Node 3 MTL PPA is sixteen years old, and the Node 2 LTL PPA is nineteen years old. In contrast, the Lab LTL PPA has run continuously since 2001, and the Lab MTL PPA, replaced in 2003, has been powered since then but rarely pumps due to the Lab's nominal Single LTL operation. After reviewing the established hardware life on-orbit, the potential design limitations could be a contributor. The PPAs were originally designed for the Lab module and operate near their design point in Lab Single Loop mode, unlike those in Node 2 and 3, which have different loop sizes and flow requirements. To maintain interchangeability and simplify spares management, the same PPA design was used across all modules, despite these differences. Overall, most PPAs have exceeded the OEM's ten-year design lifespan, but recent trends have noted that the integration of the PPAs into smaller modules has yielded anomalies not yet expressed within the Lab. Making the PFMC replaceable extends PPA life and reduces the need for complete PPA spares, lowering launch mass and stowage constraints. Adding the capability to modify and update a pump's motor controller firmware can provide the opportunity to troubleshoot and possibly fix faults within the controller. Increasing the data rate so ground teams have better insight into the controller would also be beneficial. As crewed missions venture to the Moon and beyond, these considerations become even more critical due to higher launch costs and longer resupply times. Future pump designs should prioritize modularity, enabling easy motor controller replacement by crew. This approach will improve logistics efficiency while ensuring continued pump functionality.

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