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The International Space Station (ISS) Port 1 (P1) External Active Thermal Control System (EATCS) Ammonia Leak

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From 2011 to 2017, the crew onboard the International Space Station (ISS) was at risk of dire consequences due to an external ammonia leak. Ammonia is used in the External Active Thermal Control System (EATCS) to cool the pressurized modules and external electrical systems. Engineers at NASA's Johnson Space Center (JSC) initially detected the leak in one of two cooling loops by monitoring the system ammonia inventory decay over time. White flakes seen on High Definition (HD) cameras were also thought to be associated with the leakage but not confirmed. Initially, the leak was small enough that the ammonia inventory and system operations were not in jeopardy. However, the leak began to accelerate to the point where troubleshooting and corrective action were vital to the sustainability of the ISS. Therefore, it became imperative that the leak be located and repaired for ISS operations to continue. No tools were readily available on the ISS to locate such a leak when it was initially detected, however NASA engineers were already in the process of developing a new device for this purpose called the Robotic External Leak Locator (RELL). The RELL is a robotic instrument package with a mass spectrometer and an ion pressure gauge. Initial checkout operations with RELL happened to coincide with the increasing leak, and ammonia vapors were measured around the P1 EATCS Radiator #3 flexible jumper hoses. The leak stopped after the radiator and its flexible hoses were remotely isolated from the loop and the ammonia from the isolated segment was vented to space. Astronauts conducted a spacewalk that successfully removed the hoses, which were returned to ground for further investigation. The purpose of this paper is to review the leak detection and isolation efforts, investigation results, lessons learned and the recovery plan.

Nomenclature

amu = atomic mass unit
E = 1x10
GN_2 = Gaseous Nitrogen
kg = kilogram
kPa = kilopascals
lbm = pound mass
NH_3 = Ammonia
ppm = parts per million
psia = pound force per square inch
sccs = standard cubic centimeters per second
torr = torr
ATCS = Active Thermal Control System
ATA = Ammonia Tank Assembly
DDCU = Direct Current-to-Direct Current Converter Unit
EATCS = External Active Thermal Control System
EHDC = External High Definition Camera
EVA = Extravehicular Activity
fwd = Forward

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FOD = Flight Operations Directorate
HD = High Definition
IEA = Integrated Equipment Assembly
ISS = International Space Station
JSC = Lyndon B. Johnson Space Center
LEO = Low Earth Orbit
LT = Low Temperature
M&P = Materials and Processes
MBSU = Main Bus Switching Unit
MCC = Mission Control Center
MER = Mission Evaluation Room
MT = Moderate Temperature
NASA = National Aeronautics and Space Administration
NTA = Nitrogen Tank Assembly
ORU = Orbital Replacement Unit
P1 = Port 1
PFCS = Pump Flow Control Subassembly
PVTCS = Photovoltaic Thermal Control System
QD = Quick Disconnect
RBVM = Radiator Beam Valve Module
RELL = Robotic External Leak Locator
S1 = Starboard 1
SMAC = Spacecraft Maximum Allowable Concentration
SSP = Space Station Program
TT&E = Test, Teardown and Evaluation
US = United States

I. Introduction

The External Active Thermal Control System (EATCS) is a closed loop single phase system that mechanically pumps liquid ammonia to cool the avionics, payloads and electronic equipment onboard the International Space Station (ISS). There are 2 EATCS located on ISS, one on the starboard side known as S1 or Loop A EATCS, and one on the port side known as P1 or Loop B EATCS, as shown in Figure 1. Leaks that develop in these critical cooling systems that deplete in-line tanks can ultimately result in loss of cooling which can have devastating impacts to the mission, science and crew onboard the ISS. This leakage could be initiated from many causes including but not limited to Micro Meteoroid Orbital Debris puncturing fluid line(s), seal or valve leaks, failure or cracks in welds or other components, cyclic loading fatigue after many years of operation in orbit, and many other causes. The leakage scenario discussed in this paper began in 2011 when a slow ammonia leak was initially observed from the P1 EATCS, but later in 2013 the leak rate began to accelerate. The ammonia inventory eventually began to decay exponentially, raising concerns that the inventory could drop to levels where the system would not be operational. Troubleshooting options included resupplying the ammonia and attempting to feed the leak, or attempting to find and stop the leak before ammonia inventory levels reached critical limits. Ammonia can be resupplied by replacing the P1 Ammonia Tank Assembly (ATA) with one of two spare ATAs located on a stowage platform external to the ISS. This option was not desirable since multiple Extravehicular Activities (EVAs) are required, and even once performed that could result in all ammonia inventory in the P1 EATCS

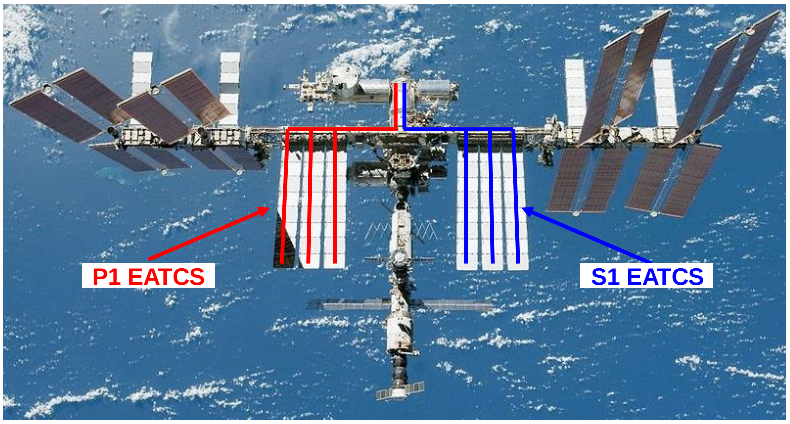

Figure 1. The International Space Station (ISS).

and two spare ATAs potentially being consumed as the leak continued to accelerate. Therefore, to protect the long term life of ISS an effort was made to determine the source of the leak and make appropriate repairs.

A major hurdle to overcome in achieving this goal was the lack of external ammonia leak detection capabilities on the ISS. From the beginning of the ISS Program, NASA had been investigating technologies and techniques to locate ammonia leaks outside ISS but the technical challenges has been significant. External coolant leak detection technologies were not explored for spacecraft like the Space Shuttle or Apollo Crew and Service Module due to their short mission duration (i.e. days to weeks). The EATCS was certified originally for a 15 year life and is expected to remain in orbit many years longer than that, and had been leak tight since their activation in 2006. Like a car, the possibility of a coolant leak occurring increases as the ISS ages. Coincidentally, a new experimental tool called the Robotic External Leak Locator (RELL) had recently been launched to ISS and was undergoing checkout just prior to when the P1 EATCS ammonia leak rate increase became apparent. RELL had the capability to interface with the ISS Robotic Arm and scan across the external ammonia systems for measurable concentrations of vaporous ammonia.

To the surprise and elation of all involved engineers and management, RELL performed beyond all expectations and indeed detected a leak in the P1 EATCS by remotely measuring low level ammonia pressure around two of the flexible jumper hose assemblies that connect one of the three deployable radiators. The leak stopped after those two hose assemblies, associated lines and the radiator were remotely isolated from the P1 EATCS and the ammonia was vented to space. Those two jumper hose assemblies have been in use since the P1 EATCS activation in 2006. It was highly desired to remove those jumper hose assembles from the ISS and return them to the ground so NASA could perform root cause failure investigation since many more similar fluid jumpers are part of the EATCS. This would help to determine if the problem was unique or a fleet issue. The two jumper hose assemblies were successfully removed by the crew during the United States (US) EVA, or spacewalk, in March 2018. The two jumper hose assembles were returned to the ground and are currently undergoing a root cause failure investigation at NASA. This paper discusses the processes involved in detecting and finding the P1 EATCS ammonia leak, the root cause investigation and lessons learned.

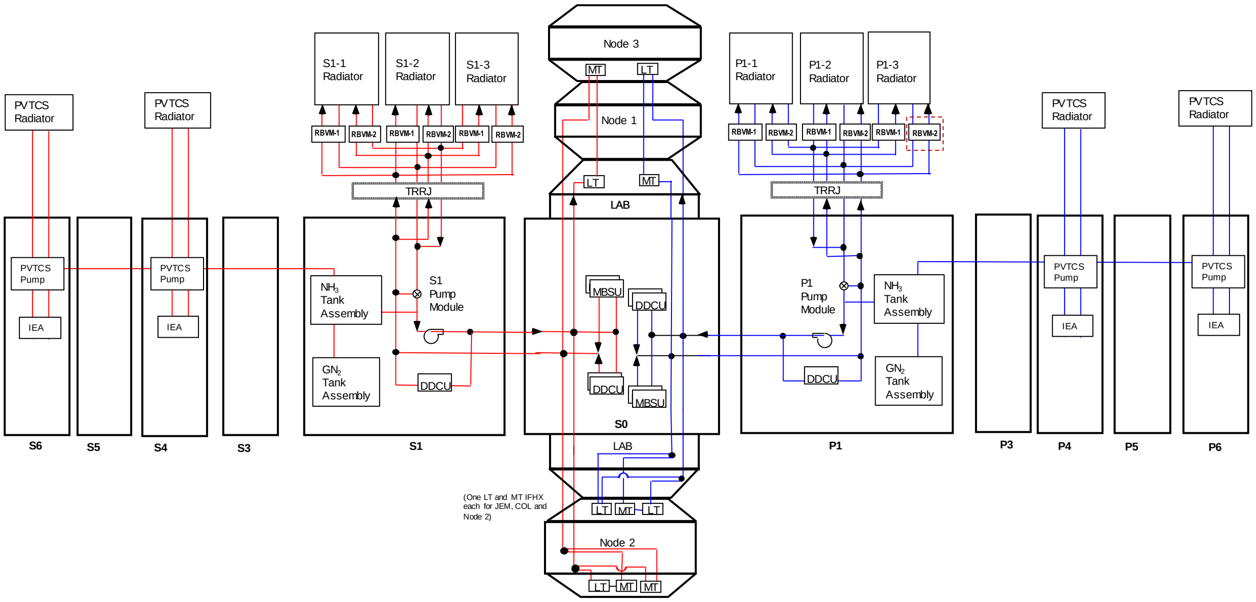

Figure 2. S1 and P1 EATCS simplified schematic.

II.   EATCS Overview

Each of the two EATCS[1] loops contain a Pump Module, an ATA, a Nitrogen Tank Assembly (NTA), three deployable radiators, multiple coldplates and heat exchangers, as shown the simplified schematic of Figure 2. Each Pump Module circulates liquid ammonia at a constant flowrate to a network of coldplates, heat exchangers, and radiators. The ATA consists of two pressure vessels filled with liquid ammonia and gaseous nitrogen separated by a collapsible bellows to provide system compliance and supply ammonia to the EATCS. The NTA is connected to the ATA and contains a volume of high-pressure nitrogen gas used to regulate the pressure in the EATCS. Ammonia supplied to the coldplates and heat exchangers collects heat, which is transferred to the three deployable radiators and rejected to space.

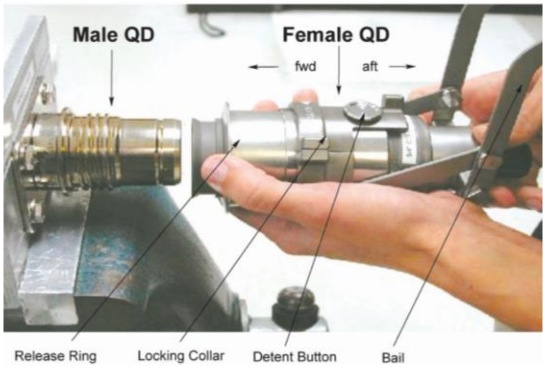

Figure 3. Male and Female Quick Disconnects

Each deployable radiator contains 2 parallel flow paths and each flow path is connected to a Radiator Beam Valve Module (RBVM). The RBVM controls ammonia flow to radiators including the ability to vent ammonia from a flowpath or isolate flow. The ATA, NTA, pump, deployable radiators, RBVM and the heat exchangers are Orbital Replacement Units (ORU). This means they have the capability of being replaced on-orbit by the crew during an EVA. The plumbing in the EATCS consists of hard tubing and flexible jumpers. Fluid Quick Disconnects (QD) are attached to each ORU to enable connection and disconnection (see figure 3), and flexible jumpers and hard tubing are used to connect them together. Each Fluid QD contains seals to secure the connection and to prevent ammonia leaks in both mated and demated conditions.

III. P1 EATCS Leak Detection and Isolation

A. Initial Leak Detection

The NASA and Boeing ATCS teams at the Lyndon B. Johnson Space Center (JSC) continuously monitor the health of the S1 and P1 EATCS by trending temperatures, pressures, flow rates and ammonia inventory levels. The ammonia leak in the P1 EATCS was detected by calculating and plotting the system mass and observing it beginning to decay over time, as shown in Figure 4. Ammonia leak rates can then be calculated using a linear least squares curve fit of the system mass over a time period. The mass in the closed system that is not leaking should be constant. However, there is not sufficient telemetry (i.e. temperature and pressure sensors) in the EATCS to have a robust system mass calculation due in part to the massive physical size and distribution of fluid system components. Different parts of the system can see different thermal environments in space and those environments can only be estimated.

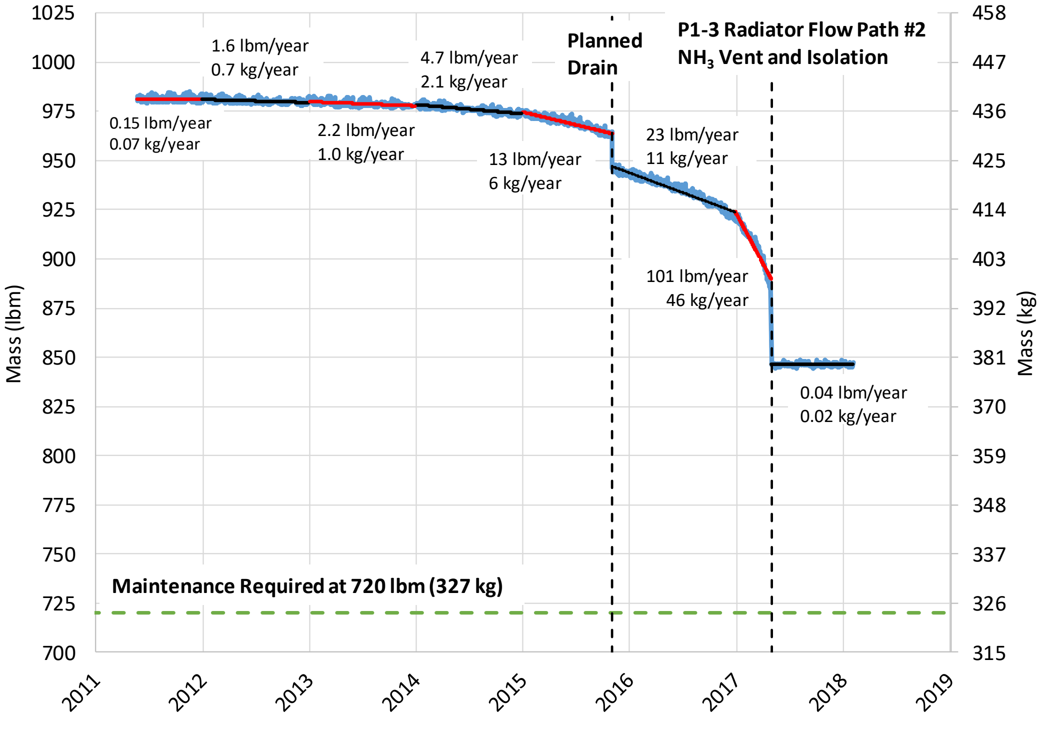

Figure 4. P1 EATCS Mass Decay over Time.

The calculated system mass oscillates due to the ammonia property assumptions made for certain volumes of the EATCS. This makes small system changes (i.e. leaks) less apparent, and the teams have to look at long term trends to provide a more accurate story of leak rates. Only long term trends (i.e. months to years) are of significance with this technique, not near term changes. Furthermore, planned system changes that add or remove significant amounts of ammonia create a discontinuity as shown in a system maintenance event in Figure 4. The planned drain event illustrated restarts the calculation after the discontinuity.

The rate of ammonia leakage was initially not a concern since it was below the EATCS leakage requirement of 7 lbm/year (3.2 kg/year). Experience has shown that leakage in the 0.5 to 1.5 lbm/year range has been typical of a tight system on ISS. The leak in P1 was tracked at a very low rate for several years before it began to accelerate, eventually trending towards exponential behavior. In 2016, ground controllers at NASA's Mission Control Center began observing "white flakes", as shown in Figure 5, from the P1 External High Definition Camera (EHDC) as the leak rate approached 30 lbm/year (13.6 kg/year). The P1 EHDC is capable of recording High Definition (HD) video outside the ISS. Pressurized liquid ammonia appears to be white and flaky when exposed to a vacuum.

Figure 5. Photo taken from the P1 EHDC pointed to space. "White Flakes" circled in red.

Though this is the first ammonia leak observed in an EATCS, it is the second ammonia leak of this type in the history of the ISS. The first ammonia leak on the ISS was from the Photovoltaic Thermal Control System (PVTCS) Channel 2B. PVTCS collects and removes heat from each solar array power channel on ISS and rejects that heat to space through four separate radiators. Based on the PVTCS Channel 2B history[2], the ammonia leak rate that was visible to cameras and crew was at a much larger rate of approximately 1000 lbm/year (454 kg/year). Earlier analysis and laboratory testing of ammonia behavior had shown that, to be visible, a leak rate much larger than seen on P1 would be required. Therefore, the frequency and amount of white flakes recorded since the first observation until the leak stopped was too low and sporadic to conclude definitively that they were associated with the P1 EATCS leak. Understanding the size and geometry of the white flakes could help conclude if they were ammonia or not. However, this could not be accomplished since the background of the images for all the white flakes was deep space and the images lack depth perception.

While watching the white flakes through the P1 EHDC, they appeared to be originating from the P1 EATCS as they moved across the screen. However, one of the spare Pump Flow Control Subassembly (PFCS) and a decommissioned ammonia system, Z1, were in the same direction of the P1 EATCS relative to the camera, as shown in Figure 6. Both the spare PFCS and Z1 contain ammonia and could be contributors to the white flakes if the ammonia in those systems began leaking to space. At the time, NASA was unable to rule out those locations as suspects since there was a lack of telemetry insight into their ammonia inventory. Thus, the P1 EATCS, the spare PFCS located on the ISS US Laboratory Module and Z1 located on top of ISS Node 1 could be the source of the white flakes. Ultimately, it could not be determined at the time of the white flakes where they were emanating from.

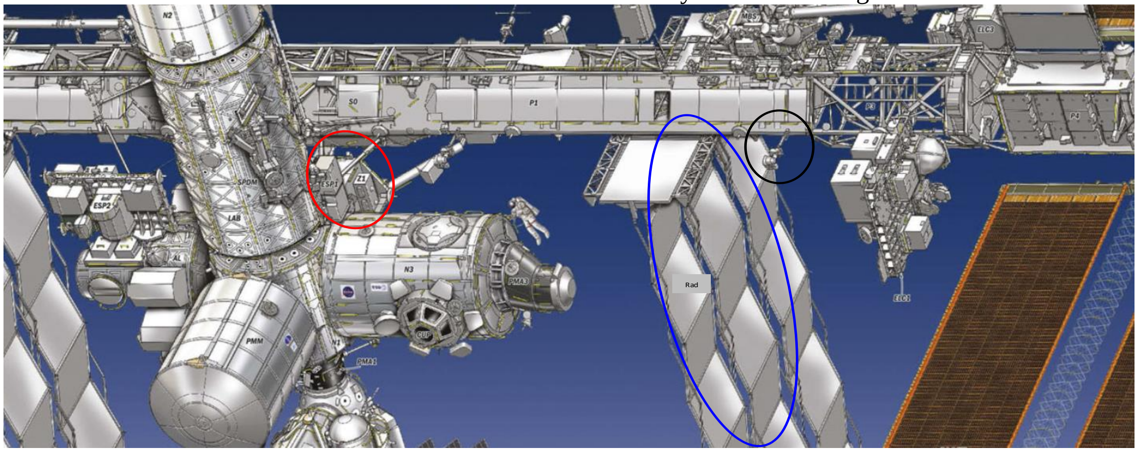

Figure 6. Location of the P1 EATCS Radiators circled in blue, Z1 and the PFCS circled in red, P1 EHDC circled in black

B. The Robotic External Leak Locator (RELL)

The decision was made to attempt to locate and stop the leak before the P1 EATCS ammonia inventory would reach levels where it would need to be replenished by replacing the ATA. Since the beginning of the ISS Program, ammonia leak location involved remotely isolating the EATCS into three segments: 1) the ATA, 2) The radiators and 3) the Pump Module plus the remainder of the system. Operators and engineers at NASA JSC would need to monitor the inventory and/or pressure decay following the isolation. This could be risky and time consuming especially while trying to maintain cooling by keeping the pump running. For instance, the radiators would not have thermal expansion capabilities while isolated and could result in hardware damage due to the thermally induced over pressure if not reintegrated into the other segments quickly.

Figure 7. RELL (circled in red) attached to the ISS Robotic Arm in December 2016.

This approach also was unlikely to isolate the exact leak location thus making any potential repair difficult or even impossible. To address this, engineers at the NASA JSC and Goddard Space Flight Center began developing and building the RELL. RELL is an instrument that can be used in conjunction with the ISS Robotic capabilities to remotely detect various gases and measure their pressures in a vacuum, as shown in Figure 7. RELL consists of a Residual Gas Analyzer and a Cold Cathode Ion Gauge and is capable of detecting molecules up to 100 atomic mass units (amu). RELL can measure pressures from standard atmosphere to as low as 1E^{-12} torr, and was certified to be able to detect ammonia leaks[3] from 1E^{-3} lbm/year (4.5E^{-4} kg/year) to 1E^{4} lbm/year (8E^{3} kg/year). A flight ready RELL unit is shown in Figure 8.

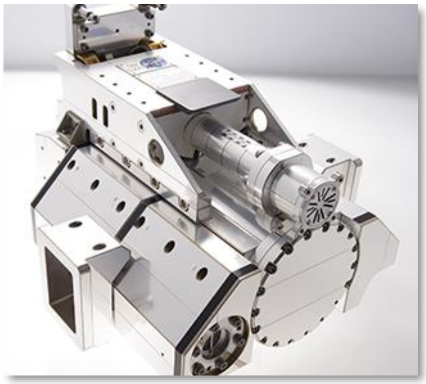

Figure 8. RELL.

RELL was developed as a technology demonstrator to investigate its possible use for leak location. RELL was launched to the ISS in December 2015 and its capabilities were successfully demonstrated in December 2016[4]. This planned demonstration test included distinguishing various gases from the natural background gasses in low earth orbit (LEO) and gathering data to determine if and how it could be used to detect external leaks. During the demonstration scans, RELL detected unexpected presence of ammonia vapor around the portside of the ISS. Over the course of a few days, RELL was remotely operated from the ground to scan for possible ammonia vapor sources near the P1 EATCS, the spare PFCS and Z1.

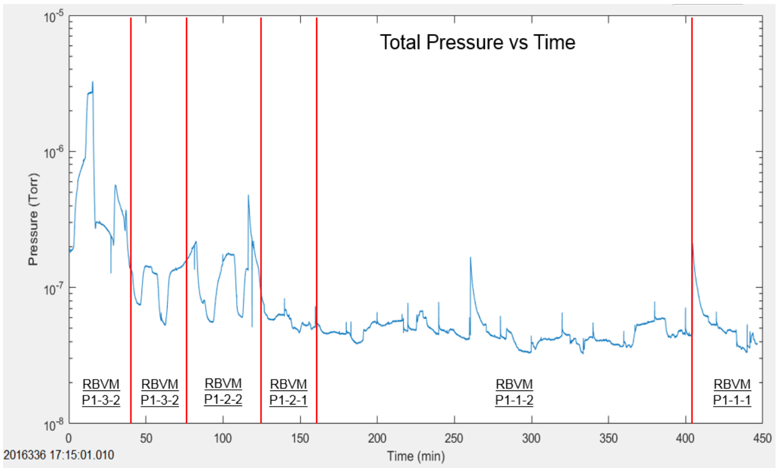

Figure 9. Total pressure versus time of all scans performed on the RBVM on the P1-1, P1-2 and P1-3 Radiators.

RELL detected significant pressure readings around the P1 EATCS. The spare PFCS and Z1 pressure readings were low and in the same order of magnitude as what was measured during the natural background scans. Though not entirely conclusive, these results increased the team's confidence that the white flakes were ammonia which had originated from the P1 EATCS. RELL proceeded to scan locations around the P1 EATCS that the teams thought could be possible sources of the ammonia leak. This included the Pump Module, the ATA and the three radiators. The highest pressure readings were around the P1-3 radiator, and a more close up scan measured similar pressures of ammonia in the area of the P1-3-2 RBVM, as shown in Figure 9 also in the dotted square in figure 2. This pressure was two orders of magnitude larger than the natural background scans. This RBVM is one of six located near the three radiator panels on the port side of ISS. P1-3-2 refers specifically to the third radiator on the port side, flowpath number two.

Figure 10. RELL scanning the P1-3 RBVM #2 Flexible Jumper Hose Assemblies.

Because of the success of the first round of remote RELL scanning, scans were again performed in the area of the P1-3-2 RBVM in February 2017, as shown in Figure 10. This included the P1-3-2 RBVM itself, the supply and return flexible jumper hose assemblies that connect the RBVM to the P1-3 radiator, and the supply and return ammonia hard-lines leading up to the RBVM that are underneath the jumper hose assemblies. Figure 11 graphically shows the RELL scanning grid and a visualization of the pressures measured using contour maps. The contour map was colored on a range from blue to yellow, with yellow corresponding to higher pressures and blue corresponding to lower pressures.

The port and starboard grids showed the highest pressure in the area of the supply and return jumper hose assemblies. However, directly underneath those two jumper hoses are supply and return ammonia hardlines coming to and from the system. Having hardware that is in close proximity or overlapping provides an additional layer of uncertainty. The data from these operations along with an understanding of the likelihood of which ammonia lines could be leaking, provided strong evidence that the source of the leak was either in the supply or the return flexible jumper hose assemblies. The strongest signature was from the radiator return line QD at the junction box of the radiator. The P1 EATCS leak rate at the time RELL completed the final scans was around 50 lbm/year (22.6 kg/year). Such an ammonia leak correlated favorably to the pressure readings from RELL based on the distance between RELL and the scan area. This gave the teams more confidence that the location of the P1 EATCS ammonia leak had been found.

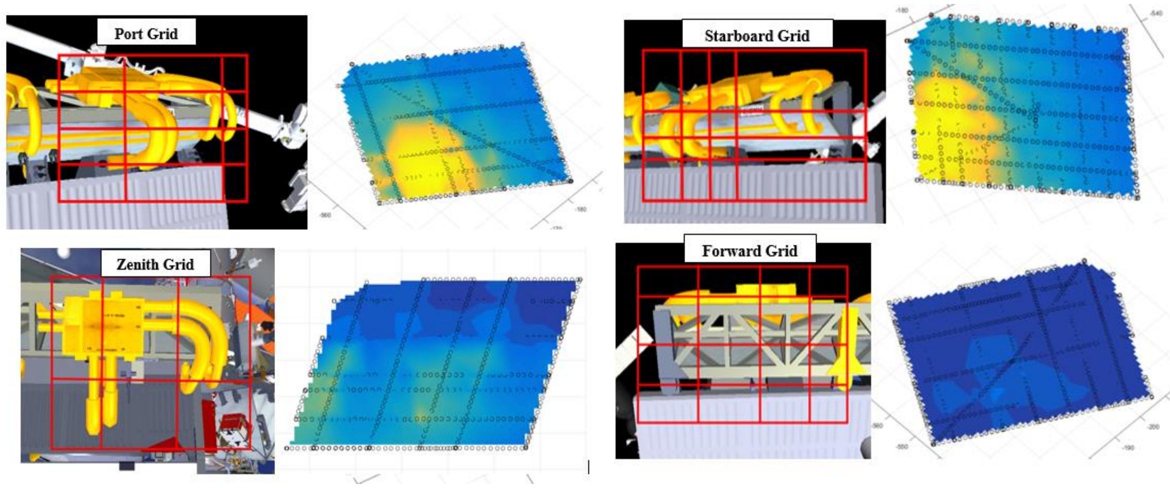

Figure 11. Pressure contour maps for each of the grid scans performed in February 2017

C. The First Spacewalk

The final RELL scans were very significant steps in efforts to locate and mitigate the source of the P1 EATCS ammonia leak. To try to better differentiate between the two flexible jumper hose assemblies and ammonia lines underneath them as the source of the leak, the ISS program agreed to have the crew perform a close-up inspection of the suspect area during an EVA, in March 2017. This involved the crew performing the following:

1. Taking HD pictures of the area
2. Obtaining HD video using an EVA modified GoPro camera
3. Inspecting and patting down the two P1-3-2 RBVM flexible jumper hose assemblies

4. Opening the Multilayer Insulation from the ammonia lines underneath the two flexible jumper hose assemblies and inspecting the area
5. Inspecting for any white flakes or other visual evidence

Figure 12. A screenshot from the EVA GoPo during the inspection of the P1-3-2 RBVM Supply and Return Flexible Jumpers.

During the EVA, no white flakes were reported by the crew, nor were there any other signs that implicated either of the two flexible jumper hose assemblies over the ammonia lines underneath them. Figure 12 is a screenshot of the footage taken during the EVA from the GoPro Camera. However, after further review of the GoPro HD video following the completion of the EVA, the teams observed multiple tiny white flakes emanating directly from one of the two hose assemblies. This was the final piece of evidence to have high confidence that the leak and the source of the white flakes was indeed from one of the two jumper hose assemblies.

D. Ammonia Venting of the P1-3 Radiator Flow Path #2

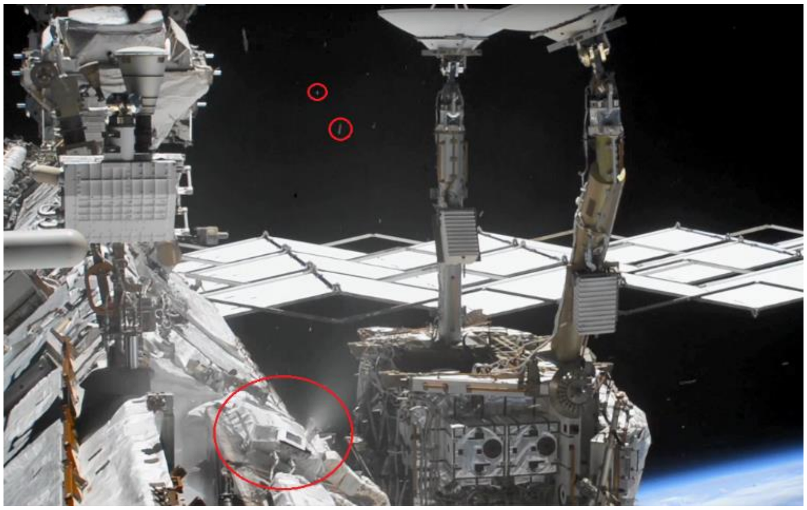

Figure 13. Ammonia vent of the P1-3 Radiator Flow Path #2. Ammonia particles and the RBVM are circled in red.

With the source of the P1 EATCS ammonia leak having been narrowed down to the two jumper hoses connecting the P1-3 radiator to the P1-3-2 RBVM the NASA JSC Engineering and Operations teams decided to isolate the hose assemblies flowpaths from the rest of the system to stop the leak. To achieve this, the P1-3-2 RBVM would have to be remotely actuated, which would isolate one of the two ammonia flow paths in the P1-3 radiator and the two jumper hose assemblies. However, just closing the P1-3-2 RBVM would result in the isolated segment becoming hydrostatically locked.

In this configuration, extremely hot or cold environmental temperatures could cause hardware damage to the P1-3 radiator or the two jumper hose assemblies. To manage this risk, the RBVMs are designed to vent the ammonia in the P1-3 radiator Flow Path #2 and the two flexible jumper hose assemblies. Following the vent, the suspected leaking flexible jumper hose assemblies would be isolated, and the mass remaining in the rest of the P1 EATCS would be monitored to determine if the mass continued to decline or if the leak had ceased.

An ammonia venting analysis was performed to determine the amount of time the P1-3-2 RBVM would need to remain in the vent position to ensure all the ammonia was evacuated[5]. The results concluded that the RBVM should remain in the vent position for no less than one hour, but the teams recommended to leave it in the vent position for no less than 24 hours for conservatism. The ammonia venting operation occurred in May 2017. Figure 13 is a screenshot of the video recorded from the ammonia venting operation. The actual time that the RBVM remained in the vent positon was around 22 hours before it was closed. The vast majority of ammonia quantity vented in the first 15 minutes.

E. Verification that the Ammonia Leak has been Found and Stopped

The teams had to wait several weeks to determine if the P1 EATCS ammonia leak had stopped after the ammonia venting and isolation of the P1-3 radiator hoses. This was due to the uncertainty and assumptions made to calculate an ammonia leak rate as mentioned earlier. After a few months following the P1-3-2 RBVM closure, the teams were confident that the ammonia leak had stopped since the mass was holding steady, as shown on the right side of Figure 4. In addition, no white flakes have been observed from the P1 cameras since the closure of the RBVM. This is partially due to limited frequency of the use of P1 cameras, but no white flakes have been observed while in use. As desired, no further troubleshooting actions were necessary (i.e. ammonia resupply by replacing the ATA) since the P1 EATCS ammonia inventory has remained above limits. For the first time in the history of the ISS or any other US space effort, a cooling system leak had been detected and located using new leak location technology of the RELL, and then isolated and shown to be stopped – with the vast majority of the effort conducted remotely from the ground!

F. Returning the Flexible Jumper Hose Assemblies to the Ground

Though the P1 EATCS ammonia leak had stopped, it was highly desired to remove the two flexible jumper hose assemblies and return them to undergo Test, Teardown and Evaluation (TT&E) to determine the root cause of the leak. Ultimately, the desire would be to replace the hoses with new or repaired hardware so that the flowpath of the radiator could be regained. The two flexible jumper hose assemblies have the capability of being removed by the crew during an EVA. Therefore, the teams proposed that their removal be performed in an upcoming EVA and subsequently brought inside the ISS to be returned on a future cargo vehicle.

Bringing the two hose assemblies inside the ISS posed a potential risk of harming the crew if sufficient amounts of ammonia remained in the two hoses after the vent and then escaped into the ISS atmosphere. NASA and Boeing engineers at JSC were confident that all the ammonia in the two flexible jumper hose assemblies except for a minor trace amount had been vented to space. However, these trace amounts could not be neglected due to the hazards associated with bringing ammonia into the pressurized volume of the ISS. There are small volumes inside the two hose assemblies where traces of ammonia vapors could theoretically be trapped.

Each end of the jumper hose assemblies have QDs, and these QDs each have primary and secondary seals against leakage. The volumes between the primary and secondary spool seals are in hydraulic connection with the ammonia when the QDs are connected and open. The potential for one or more hydraulically locked volumes occurs when the QDs on the two hose assemblies were closed during the EVA potentially trapping residual ammonia between the primary and secondary spool seals.

An assessment was performed to determine the maximum amount of ammonia that could exist between the primary and secondary spool seals in the QDs on both the supply and return hose assemblies. The Spacecraft Maximum Allowable Concentration[6] (SMAC) of vaporous ammonia allowed in the ISS pressurized modules is 30 ppm. The assessment concluded that the worst case possible amount of trapped ammonia could result in 12 ppm in the smaller airlock space in the ISS only if all four QDs' trapped volumes were filled with liquid ammonia and all four then spontaneously released that ammonia in the airlock at the same time. This is below the 30 ppm SMAC limit and an acceptable risk due to the exceedingly small likelihood of actually occurring.

To ensure confidence that the two flexible jumper hose assemblies were indeed vented of ammonia in addition to what could be trapped in the QD, it was recommended that a second vent be performed no later than a week prior to the EVA. The P1-3-2 RBVM would remain in the vent position for the entire week leading up to the EVA. With this plan, the ISS Program approved having the two hose assemblies removed on the next EVA so they could be returned to ground for TT&E. The two jumper hose assemblies were successfully removed during an EVA in March 2018 with no issues, and then returned to the ground later that year and delivered to NASA and Boeing for TT&E.

IV. TT&E of the two Flexible Jumper Hose Assemblies

The first step in the TT&E was to conduct a visual survey of the two flexible jumper hose assemblies. For the supply hose assembly, there were no signs of structural issues for the jumper hose itself. The two QDs on each end of the supply hose assembly appeared almost pristine, as shown in Figure 15. However, this cannot be said for the return flexible jumper hose assembly. Though no structural issues were observed for the jumper hose itself, there was noticeable brown colored residue found on the secondary spool seals on both QDs, as shown in Figure 16. This was observed on the visible exposed seals, however the aft primary and secondary spool seals located on the aft end of each QD cannot be observed without disassembly.

A sample of the residue was taken and sent to a Materials and Processes (M&P) lab where detailed examination could be conducted. Lab results revealed the material consisted of non-volatile residue (NVR) which included silicone grease classified as polydimethylsiloxane, and many other compounds typically found in NVR for systems of this nature. While the ammonia used in the EATCS is certified to a 99.998% purity, the amount of NVR found in the sample was consistent with the amount that is allowed in ammonia. When ammonia leaks through seals or other interfaces into the vacuum of space and changes phases from liquid to gas, the NVR is typically left behind at the leak site. The larger quantity of residue found in these QDs indicated the possibility of their role in the P1 EATCS leak, but were not a conclusive indicator of the prime leak site.

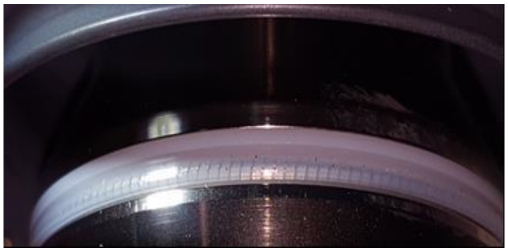

Figure 15. Supply Hose Assembly QD Forward Secondary Seal.

The next phase of TT&E was to perform accumulation bag leak tests on both the supply and return flexible jumper hose assemblies. This involved bagging the hose and the QDs separately using a procedure where accumulated helium inside sealed bags can be compared to standard calibrated leaks to yield true indicated leak values for each isolated section. A leak rate can then be measured and compared to the leakage requirement of $1E^{-4}$ sccs of Helium at 500 psia (3447 kPa) and standard atmospheric temperature. The supply jumper hose assembly barely failed the leakage requirement at 1.4E-4 sccs of Helium @ 500 psia. However, the return hose assembly significantly failed the leakage requirement. QD F140 (connected to the RBVM) failed the leakage requirement at 2.8E-3 sccs of Helium at 500psia. QD F128 (connected to the radiator) failed the leakage requirement at 1.91 sccs of Helium at 500 psia (3447 kPa). This was believed to be the same order of magnitude leak rate that was calculated from the P1 EATCS before the leak stopped upon closure of the P1-3-2 RBVM.

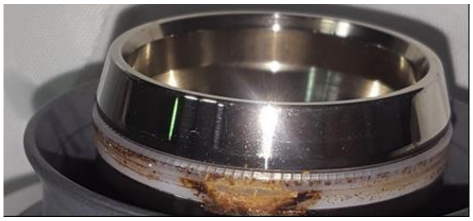

Figure 16. Return Hose Assembly QD Forward Secondary Seal.

An additional bagged leak test was performed on the QD F128 to determine if the front or aft end of the QD was the leak source since there are multiple seals and multiple leak locations within a QD. The forward half of the QD F128 failed the leakage requirement at 2.2E-1 sccs of Helium at 500 psia and the aft half failed at 0.5 sccs of Helium @ 500 psia. This suggested that the primary and secondary aft spool seals were the major source of the P1 EATCS leak. This was surprising since such a leak had never been observed on aft seals, or any other continuously sliding seal. Inspection of the primary and secondary aft spool seals could not be performed without disassembly. Therefore, disassembly of QD F128 and QD F140 and evaluation of the aft spool seals would help determine the root cause of the seal failure and any remedial actions.

This failure investigation of the removed failed QDs from the return hose assembly is currently underway, and results from this aspect of the effort are expected to yield important information as to what the future might hold for similar leaks on ISS.

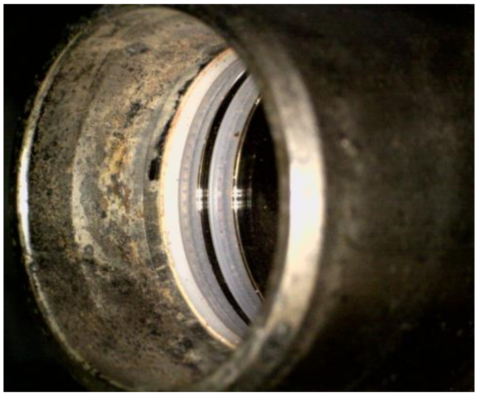

Figure 17. Return Flexible Jumper Assembly QD Aft Spool Seals.

The results of the QD F128 failure investigation could, at minimum, result in the following:

1. Determine if the failure was unique or if this is a leading indicator of a fleet issue.
2. Determine if the failure on QD F128 could have compromised its Male QD counterpart located on the P1-3 radiator still on ISS.
3. Identify possible design changes to QDs for future applications.
4. Reassessment of the current sparing posture of these types of QDs and jumpers

Disassembly of the failed QDs took place with the help of the hardware vendor in March 2019, and initial indications are that the suspect aft spool seals were indeed responsible for the majority of the leakage experienced on ISS. A significant quantity of brown deposits, as shown in figure 17, were seen just down-stream of the enclosed aft seals and further analysis of the deposits and examination of surfaces is planned in the near future. Details on this analysis and more discussion of how those results might impact future operations on ISS are expected to be the subject of a follow-on paper.

V. Lessons Learn and P1 EATCS Recovery

After many years of planning to deal with ammonia leakage on ISS where specific leak location is not known, the P1 EATCS leak has given the technical teams an opportunity to try out and explore various approaches. RELL was added to the ISS toolset just in time to be instrumental in the detection of such external ammonia leaks. Future external leak troubleshooting steps and procedures will include the use of RELL to even a greater degree based on experiences gained recently in its use. A second RELL has been built and was successfully launched to the ISS in April 2019, which adds redundancy to leak location abilities. In addition, an external stowage platform for RELL is being built now and is to launch in early 2020 that will enable both RELL units to remain outside where they can quickly be accessed for use in leak location activities without involving the crew or airlock resources.

To regain full capacity of the P1 EATCS radiator heat rejection system on ISS, it was highly desired to obtain replacement hose assemblies and get them relaunched to ISS sooner rather than later. The ISS Program approved the refurbishment of both jumper assemblies that were returned from ISS. For the supply hose assembly, refurbishment was fairly straightforward since it was basically in pristine condition and only needed retest and leakage verification prior to relaunch to the ISS. For the return path jumper hose, the QDs from both ends were removed and replaced with new QDs, but the jumper hose itself was cleared to be reused as-is. Both refurbished hoses were launched in April 2019 and are planned to be reinstalled via EVA in 2020. Assuming reinstallation goes well and no additional problems are experienced, it is hoped that this will regain the use of the additional cooling capacity of the P1-3-2 radiator flow path.

VI. Summary

This paper discusses the P1 External Active Thermal Control System (EATCS) ammonia leak that was initially identified on the International Space Station (ISS) around 2011. The rate of ammonia leakage was initially not a concern since it was below the system leakage requirement of 7 lbm/year (3.2 kg/year), but the eventual rate of increase was concerning and it later reached almost 101 lbm/year (46 kg/year) before the leak was stopped by isolation. The Robotic External Leak Locator (RELL) was built and launched to the ISS to detect and help locate ammonia leaks using the ISS Robotic Arm and remote ground operator control without constant crew involvement. RELL pinpointed the ammonia leak to the two flexible jumper hose assemblies connecting the P1-3 deployable radiator to the P1 EATCS via the P1-3-2 Radiator Beam Valve Module. The ammonia inside the two hose assemblies and the P1-3 Radiator Flow Path #2 was isolated and vented to space in 2017. This stopped the leak and an Extravehicular Activity was conducted to remove the two flexible jumper hose assemblies so they could be returned to ground for further Test, Teardown and Evaluation.

After the two hose assemblers were returned, it was determined that one out of the two Quick Disconnects (QD) located on the return hose assembly was the major source of the P1 EATCS ammonia leak. Both QDs were found to contain significant brown deposits believed to be non-volatile residue from the ammonia leaking through them. The root cause of the ammonia leak in that QD is still unknown as the failure investigation is still ongoing. Both jumper hose assemblies have been refurbished, relaunched to ISS, and are currently stored inside awaiting an upcoming EVA opportunity to be reinstalled. Results from the root cause failure investigation may have significant impacts on ISS operations and are expected to be published in a later paper.

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