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Coolant Leak from ISS External Active Thermal Control System (EATCS) – An Examination of Most Probable

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The Port (P1) and Starboard (S1) External Active Thermal Control Systems (EATCS) are single phase, mechanically pumped ammonia loops that operate independently to cool majority of the hardware and payloads onboard the International Space Station (ISS). A slow ammonia leak was detected using pressure and quantity telemetry five years after the P1 EATCS was activated. The leak gradually accelerated to a rate that locating and isolating the leak became imperative to maintain cooling capability. Partial pressure measurements from the Robotic External Leak Locator (RELL) scan surveys narrowed the search to the supply and return jumpers connecting one of three radiators to the system. Subsequently, the ISS crew performed high-definition video surveys during an Extravehicular Activity (EVA), or spacewalk, and ammonia flakes were observed projecting from the jumpers. Thus, the ground teams were confident that the culprit of the ammonia leak were the jumpers. The ammonia leak stopped after ground teams remotely isolated and vented those jumpers and associated radiator. Both jumpers were removed and returned to the ground, and a root cause investigation was conducted. A calibrated leak test determined the bulk of the ammonia leaked through a pair of seals in a Quick Disconnect (QD), or connector, on one end of the return jumper. The return jumper QD was dissected, visually inspected, chemically tested and evaluated. The results indicated the most probable cause of the accelerating ammonia leak was due to defective seals, plating delamination underneath the seals, and on-orbit thermal cycles exacerbating the delamination. Both jumpers were refurbished, relaunched to the ISS, and scheduled to be reinstalled during an EVA in 2022. It appeared the issue was unique, but recently the S1 EATCS is showing signs of an accelerating ammonia leak, and RELL scans narrowed the source to a similar pair of radiator jumpers.

Nomenclature

ATCS = Active Thermal Control System
CT = Computerized Tomography
DSC = Differential Scanning Calorimetry
EATCS = External Active Thermal Control System
EDS = Energy Dispersive X-Ray Spectroscopy
EVA = Extravehicular Activity
FT-IR = Fourier Transform Infrared
fwd = Forward
GN_2 = Gaseous Nitrogen
ISS = International Space Station
JSC = Lyndon B. Johnson Space Center
kg = kilogram
kPa = kilopascals
lbm = pound mass
LEO = Low Earth Orbit
M&P = Materials and Processes
MMOD = Micrometeoroid and Orbital Debris
NASA = National Aeronautics and Space Administration
NDE = Nondestructive Evaluation
NH_3 = ammonia

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NH_4OH = ammonium hydroxide
NVR = Non-volatile Residue
O_3 = Atomic Oxygen
P1 = Port 1
ppm = parts per million
psia = pound force per square inch
QD = Quick Disconnect
RBVM = Radiator Beam Valve Module
RELL = Robotic External Leak Locator
S1 = Starboard 1
sccs = standard cubic centimeters per second
TIM = Technical Interchange Meeting

I. Introduction

The Port (P1 or Loop A), and Starboard (S1 or Loop B), External Active Thermal Control Systems (EATCS) are single phase, mechanically pumped ammonia loops that operate independently to cool the pressurized modules and external avionics on the International Space Station (ISS). Five years after activation, the P1 EATCS experienced an accelerating coolant leak, and a series of on-orbit activities[1] (i.e., spacewalks and robotic leak locating surveys) helped narrow the source to a pair of jumpers that supply coolant to and from one of three P1 EATCS radiators as shown in Figure 1. The pair of jumpers, or supply and return jumpers, were too physically close to differentiate which one was leaking, but the radiators and jumpers are isolatable using the Radiator Beam Valve Module (RBVM) that controls flow to and from the radiators. The leaked stopped after the radiator and jumpers were vented and isolated, but this resulted in reduced cooling capability. Restoring that radiator is necessary to support the future heat rejection needs, but spare jumpers are not stored on the ISS due to the varying sizes and unique geometries.

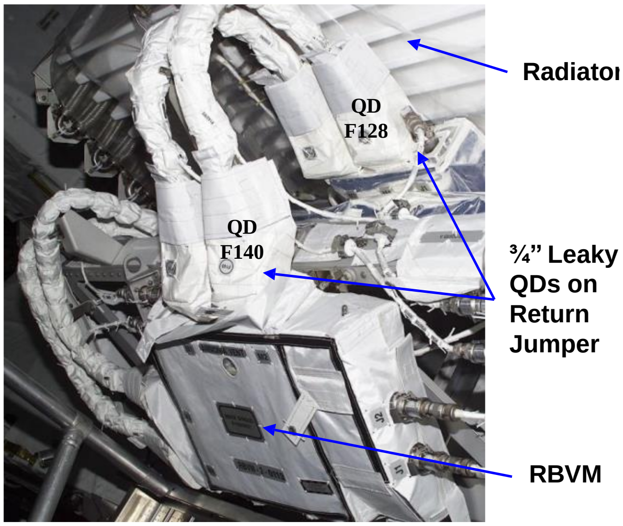

Figure 1. Radiator Jumper connected to a radiator and the Radiator Beam Valve Module (RBVM) that control flow to and from the radiator

Following being returned to the ground from ISS, several calibrated leak tests were performed on both jumpers and leaks were found in the fluid connectors, or Quick Disconnects (QDs), on both ends of the return jumper[1]. No issues were found with the supply jumper. Further leak tests were performed, and the highest leakage was measured near a pair of seals inside QD F128 that connects the return jumper to the radiator as shown in Figure 1. The QDs on both ends of the return jumper were removed, disassembled for further evaluation, and replaced with pristine QDs, using an inventory of spare parts that are stored on the ground

Both the supply and return radiator jumpers were refurbished, launched, and reinstalled during an Extravehicular Activity (EVA), or spacewalk which occurred in March 2022. There are over two hundred similar QDs as part of each the S1 and P1 EATCS, and twenty-four are of same type and size as the QDs on the return jumper that was found to be leaking. Understanding the failure that caused QD F128 to leak and determining if it was unique or common to the other QDs was important to assess the long-term sustainability of the EATCS. This paper discusses the findings, conclusions, recommendations, and observations from this failure investigation.

II. ISS External QD Overview

QDs are used throughout the EATCS to connect hardware (i.e., pumps or radiators) to fluid lines and allows the hardware to be removed or replaced by the crew. Generally, replaceable hardware like the radiator jumpers have female QDs on each end, and they mate to male QDs on the fluid lines like shown in Figure 2. Inside each QD are seals to provide for a leak free connection between various parts, allow ammonia to pass through, and prevent ammonia from leaking to space. Parker Symetrics, now Parker Stratoflex, partnered with NASA to design and produce all the ISS EATCS QDs. The QD body is made of stainless steel and Inconel, and some of the components are coated with Nedox, a nickel-based coating added for increased durability and reduced friction.

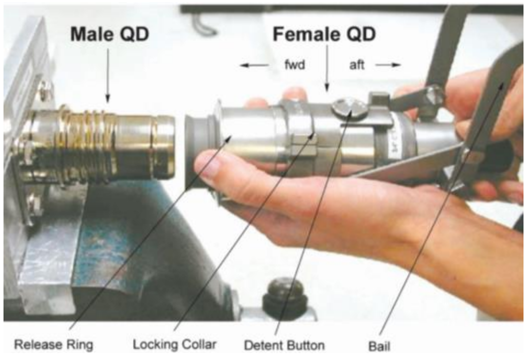

Figure 2. Male and Female Quick Disconnects

There are primary and secondary seals inside the forward and aft ends of each QD as shown in Figure 6 and 5, respectively, and made from a plastic material reinforced with an internal support spring. Several tests were performed during the development of QDs that verified the design and material are compatible with ammonia and to minimize leakage. The QDs were qualified to operate and cycle between temperatures and pressures of -100 and 155 Deg F (-148 to 68 Deg C), and 30 to 500 psia (207 and 3447 kPA) for a minimum of 10 years while in service. All the radiator return jumper QDs on the S1 and P1 EATCS experience similar temperature and pressure variations of -40 and 0 Deg F and 100 and 390 psia (689 and 2689 kPa), respectively, while in service on-orbit, which is within the qualification limits. The allowable ammonia leakage for QDs is $1x10^{-4}$ standard cubic centimeters per second (sccs) at standard atmospheric condition. Though the radiator return QDs passed this requirement prior to flight, QD F140 and F128 were measured to be leaking at $2.8x10^{-3}$ and 0.5 sccs, respectively, at the same conditions during leak testing as part of this investigation.

If a QD fails the leakage requirement during build, typically cleaning or replacing the primary and secondary forward seals would remedy the issue. These seals are easier to access during final assembly unlike the primary and secondary aft seals that are only accessible when the QD is disassembled. A thermal vacuum leak test is performed after QDs are built and again in an ambient condition test after final assembly into a hardware like the radiator jumpers. However, this leak testing does not include measuring leakage from the forward and aft ends of each QD separately like performed during this investigation. It was planned that any defects that would cause the QD to leak would be identified and repaired during inspection throughout the build and processing of ISS elements for launch, however there was an accepted risk that with some seals (such as primary and secondary aft seals) where independent verification wasn't possible.

III. Failure Investigation Plan and Fishbone Diagram

NASA partnered with the ISS prime contractor, Boeing, and the QD manufacture, Parker Stratoflex, to determine the most probable root cause of the QD leak. A fishbone type diagram was created to list the potential contributors to the leak as shown in Figure 3, and the failure investigation involved assessing each of the potential contributors through visual inspection, chemical evaluations, nondestructive evaluation (NDE), and destructive evaluations. First the QDs were disassembled by Parker Stratoflex, then inspected by the naked eye and under magnification using a borescope and a stereo microscope. Material samples were then taken by NASA Johnson Space Center (JSC) and Boeing Huntsville Materials and Process (M&P) labs and evaluated using Energy Dispersive X-Ray Spectroscopy (EDS), Fourier Transform Infrared (FT-IR) and Computerized Tomography (CT) scanning to see what information could be gained.

An ammonia immersion test was performed at NASA's White Sands Test Facility (WSTF) to evaluate the non-volatile residue (NVR)[1] found inside the QDs after they were disassembled, and additional stereo microscopy was performed. The seals were removed, and underwent compression testing, gas chromatography–mass spectrometry (GC-MS), and Differential Scanning Calorimetry (DSC) testing. The results were compared to a pristine seal to determine any change to the material or fluid properties. The likelihood of each potential cause contributing to the QD leak is discussed in the next section of this paper.

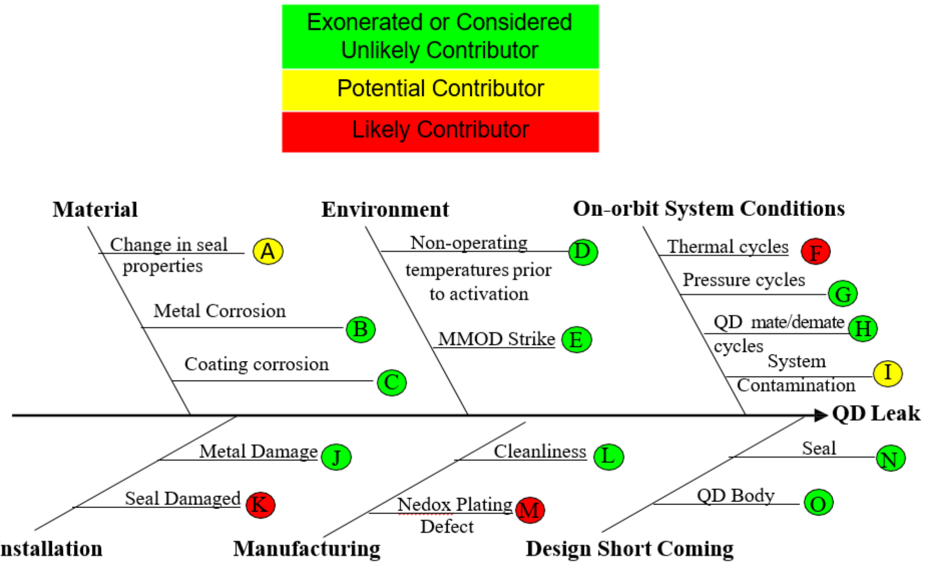

Figure 3. Fishbone Diagram of Potential Contributors to the QD leak

IV. Findings

A. Exonerated or Considered Unlikely Contributors to the QD Leak

Contributors B through E, G through H, J, L, O and N shown in Figure 3 were exonerated or considered unlikely as contributors to the QD leak. The QDs are made of 15-5 stainless steel and Inconel 718 with thick walls, and any cracks to the material because of corrosion, installation issues or collisions with Micrometeoroid and Orbital Debris (MMOD)[3] could cause a leak.

However, this was not observed from the imagery inspections or chemical evaluations. Prior to when the radiators were filled with ammonia and the EATCS were activated in 2006, all the radiator jumpers and QDs contained a GN_2 pad pressure, and the exposure temperatures predicted to be near the upper QD limit as shown in the Figure 4. These

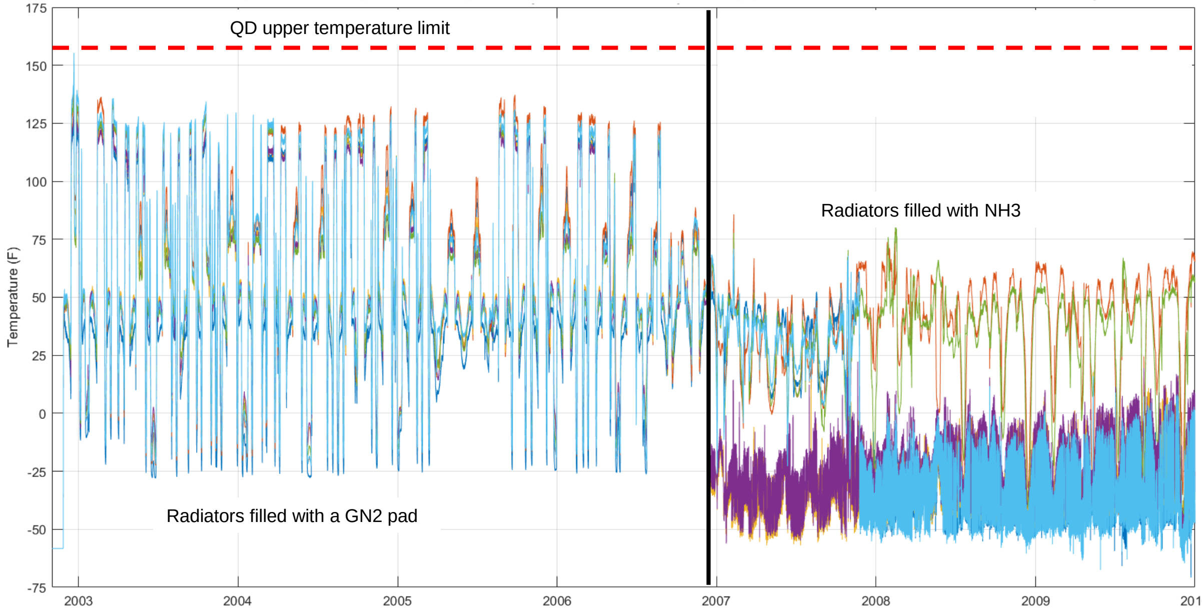

Figure 4. Temperatures from each of the P1 EATCS radiators. Radiators were filled with GN2 until Mid-2006 then filled with ammonia and activated.

temperatures were expected due to the vehicle configuration and orientation, empty flowpath conditions, and fluid properties unlike when the when the system is in operation with flowing ammonia. Similarly, the QDs were also exposed to wider pressure variations during this time since the pressure change is directly proportional to the temperature changes, but a telemetry review concluded that the pressures and temperatures were within limits. Thus, it's unlikely that pressure and temperatures variations alone would cause any damage to the QDs.

Some components of the QDs are plated with Nedox, and development testing has shown that Nedox is expected to be resistant to corrosion when exposed to ammonia. However, it is not corrosion resistant to ammonium hydroxide (NH_4OH) solutions, which is produced when the ammonia has a sufficient concentration of water to react with. The oxygen in the water reacts with ammonia and can corrode the Nedox causing ammonia to leak by compromising sealing surface finish, but the amount of moisture or oxygen allowed in the ammonia specification is not enough on its own to produce NH_4OH. It requires oxygen and moisture from an external source, for instance from the environment around the QDs, to react with ammonia at the seal interface for a corrosive reaction to occur.

The environment around EATCS QDs is obviously a vacuum, and there is no path for cabin atmosphere to reach external QDs. Therefore, conditions are not met for corrosion from those sources. Since the QDs are located external to the ISS, Atomic Oxygen (O_3) from the Low Earth Orbit (LEO) environment surrounding the ISS could be another source; however, it cannot produce NH_4OH. Thus, it is less likely that corrosion was a contributor to the QD leak.

Cycling QDs, or mating and demating, causes many seals inside the QD to slide back and forth on sealing surfaces, and repeated cycling could degrade the seals through wear sufficiently to induce a leak path. However, all the EATCS QDs were qualified to 100 mate and demate cycles, and the QD that leaked on-orbit only experienced a fraction of the qualification limit. With regards to surface contamination, the surfaces of the QDs were cleaned to requirements similar to MIL-STD-1246 Level 200F[4] prior to launch, and several tests were performed that verified cleaning to this level is sufficient to prevent damage from contamination when wetted with ammonia. There was no evidence from the materials assessment (i.e., EDS, FT-IR) that the cleanliness of the QD surfaces or the ammonia purity requirements were a contributor to the QD leak. As mentioned earlier, the P1 and S1 EATCS have been operating and flowing with ammonia since 2006. No other accelerating leaks have been detected from telemetry at the time of this investigation, and it did not appear that there was a generic problem affecting all QDs.

Thus, it was concluded the QD design (i.e., body, seals, and material) is acceptable, and likely not a contributor to the QD leak. NDE and destructive evaluation was performed on seals removed from the leaky QD and on new unexposed seals to determine any changes to material and fluid properties or degradation. Results from the CT scanning showed a 10% decrease in the average seal dimension but results from the CT and DSC testing showed no significant change in material or fluid properties. Thus, no clear sign of seal degradation that could cause leaks to develop and implies there are no design insufficiencies, and not likely a significant contributor

B. Likely and Potential Contributors to the QD Leak

B.1. Contributor K – Seal Defect During Installation

As mentioned earlier, a calibrated leak test found the highest leakage occurred near the aft seals on QD F128[1], and there are primary and secondary seals located on the forward and aft end of the QD as shown in Figure 6 and 5, respectively, After the QD was disassembled, stereo microscopic images found what appeared to be a probable damage, or defect, on both aft seals on QD F128, and the defect goes across the seal in the direction that would allow ammonia to leak to the outside environment as shown in Figure 5. This type of defect has been observed during ground inspections post seal installations on other QDs while the QD is being assembled at the manufacturer and are typically replaced at that time prior to final factory testing. A pristine seal would not have this defect as shown in Figure 5, and this defect was not observed on any of the other seals in QD F128 or F140.

Installation of this style of seal is difficult to accomplish and it is not uncommon that multiple seals are consumed before a and successful installation. Typically, the QD would fail the leakage required during acceptance testing if any defects are missed during seal inspection. Processing records show that QD F128 did fail the leakage requirement during final leak testing before launch but passed all Parker factory testing originally. The QD passed the leakage requirement after the primary and secondary forward seals were replaced and was accepted for launch. However, this leak test included the entire QD and all seals, since the aft seals cannot be individually leak tested as mentioned earlier, which is an accepted risk for all QDs.

Ammonia would have to breach the primary and secondary aft seals to leak out to space. Since the calibrated leak test during the failure investigation showed the highest leakage coming from the aft seals, the failure assessment team hypothesized that at least one of the two aft seals was performing well after final testing prior to launch. The other seal could have been leaking undetected, but still pass the leakage test. Therefore, the leading theory is that the aft seal defect was a likely a contributor to the leak of QD F128.

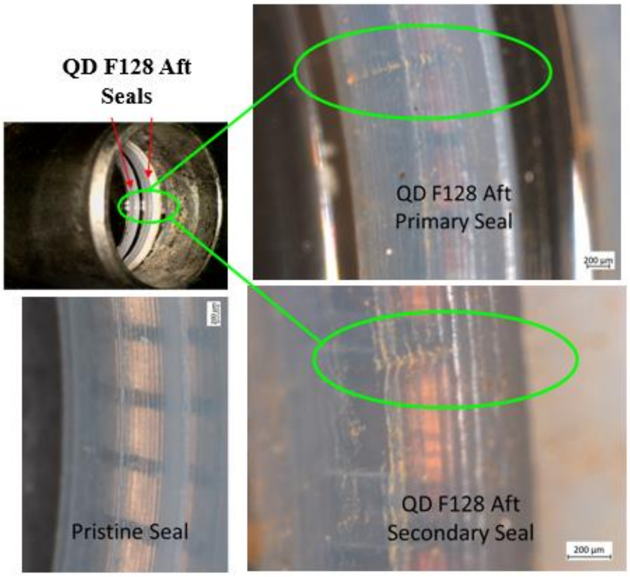

Figure 5. QD F128 Aft Seals Defect Compared to a pristine Seal (QD).

B.2. Contributor I - Fluid System Contamination

Visual inspections of QD parts were conducted at various stages of the failure investigation, and brown NVR[1] on the forward secondary seals on both QD F128 and F140 were observed after the jumpers were returned the ground as shown in Figure 6. Samples of the NVR was chemically evaluated, and the results found the constituents and quantity to be as typically expected, and generally within the allowable limits per the ammonia purity specification[1]. The presence of NVR on the seals were expected because the ammonia vaporizes as it passes through the leak path and into a vacuum leaving behind residue. Past observations and testing have shown that NVR can be deposited on and adhere to cold surfaces preferentially. Radiator jumper QDs are exposed to typically -40 to 0 Deg F (-40 to -18 Deg C) temperatures while in service on-orbit, which is cold enough for the NVR to deposit on surfaces downstream of leak sites and seals which is consistent with what was observed. Over time this process continued resulting in a significant quantity of deposits, continuing until the leak was stopped by venting the ammonia from the radiator flow path and jumpers.

The NVR deposits alone were likely not enough to have induced a leak path but cycling the QD with the NVR on the seal surfaces could do so. Though pristine QDs were installed on the refurbished return jumper, it is expected that the sealing surfaces on the RBVM and radiator QDs that mate to new pristine female QDs on the jumper may contain the NVR deposits also. This could be an issue when the refurbished return jumper is reinstalled as installation requires cycling the QDs, and the seals on the pristine female QDs on the return jumper would slide across the sealing surfaces on male QDs that may have NVR on surfaces. Contact between the new QD seals on the refurbished jumpers and male surfaces with deposits may result in damage and could introduce a new leak path. Conceptually, wetting the sealing surfaces on the RBVM and radiator QDs with ammonia should redissolve the NVR back into solution and reduce risk of damage, but only if this could be achieved after installing the refurbished jumpers, and before cycling the QDs.

This technique would have to be performed during the EVA to install the refurbished jumpers, and the amount of time for NVR to redissolve would be limited. To evaluate feasibility, the failure investigation team performed an ammonia immersion test on samples from the leaky QDs to determine if the deposits would dissolve back into solution and how long that would require. The test included soaking the disassembled QD F128 with ammonia for increasing durations, with and without agitation. Unfortunately, it was found that the NVR was not readily dissolvable and would take several hours to completely dissolve back into solution, which is longer than the amount of time available to perform during the EVA to install the refurbished jumpers. Therefore, wetting male QDs during the EVA would not be beneficial, and the risk of possibly introducing a new leak path was accepted due to the low likelihood and based on engineering judgement.

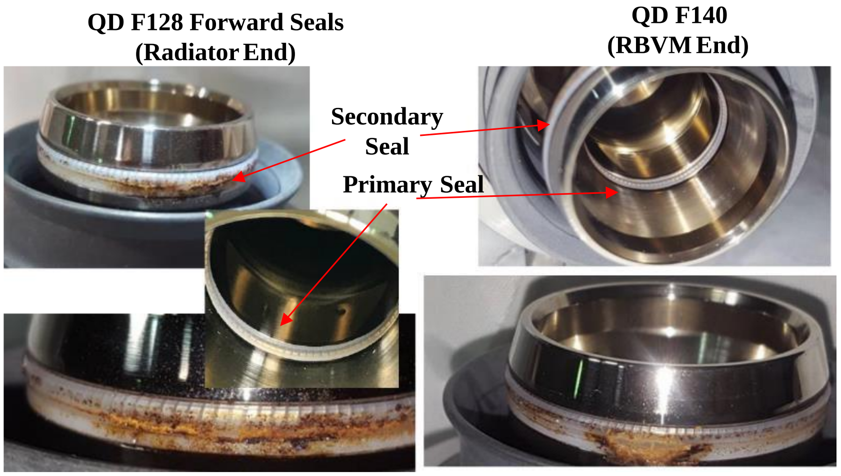

Figure 6. Brown NVR shown on the QD F128 and F140 Secondary Aft Seals

B.3. Contributor M - Nedox Plating defect

Stereo microscope imagery was performed on the leaky F128 QD following the ammonia immersion test, and Nedox plating delamination and pitting was found on aft sealing surfaces. Delamination wasn't observed prior to the ammonia immersion as it was hidden under areas with NVR, and some locations appeared to align with the location of defect found on the aft secondary seal as shown in Figure 7. The consequences of Nedox delamination could be to produce a path for ammonia to leak to space especially if it's located underneath a seal. Therefore, this was considered a likely a contributor to the QD leak. Nedox adhesion issues were observed during ground acceptance testing of two similar radiator return QDs prior to flight and were from the same manufacturing lot as the leaky QD F128, and all the other radiator return QDs in service on-orbit, and five ground spares.

In 2000, Boeing M&P led an evaluation of the delamination issue with the vendor, Parker Stratoflex, and determined that the likely cause of the adhesion issues was due to contamination of surfaces on a few components during plating. At the time, the experts believed this issue was not fleet wide because it should be detected during acceptance testing or inspections during preparation for flight. The two QDs with the Nedox adhesion issue were scrapped, and the other radiator jumper QDs, including F128, were launched based on inspections that were performed. The corrective actions at the time for plating issues led to the modifications of the plating process to reduce the likelihood of causing this issue for future QDs, but it is possible that Nedox adhesion issues were present on the leaky QD F128 and had gone undetected until the delamination started to occur while in service on-orbit. Therefore, it is considered likely that Nedox delamination contributed to the QD F128 leak.

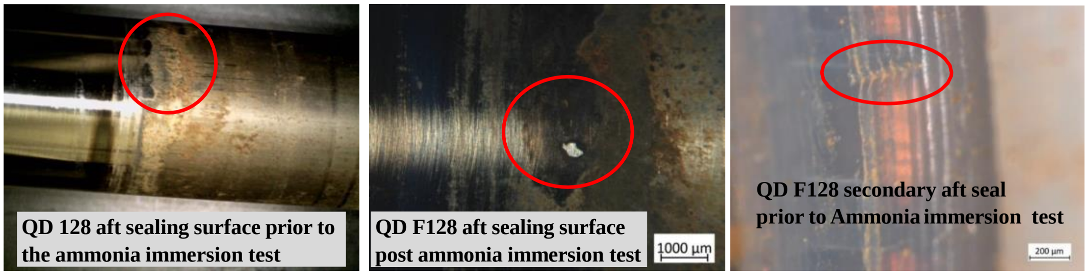

Figure 7. QD F128 sealing surface prior (left image) and after (middle image) of the ammonia immersion test. Defect found on the aft seal (right image) coincides with delaminated area (middle image)

B.4. Contributor F - On-orbit Thermal Cycles

As discussed earlier, the typical on-orbit operating temperature of the ammonia flowing through all the radiator return jumper QDs range from -40 to 0 Deg F (40 to -18 Deg C). While this is well within the design limits for QDs of -100 and 155 Deg F (-73 and 68 Deg C), thermal cycling of this magnitude could aggravate the Nedox plating issues found on QD F128 ultimately resulting in delamination and failure of the coating under seals. This is considered a likely contributor to why the P1 EATCS ammonia leak accelerated over time while QD F128 was in service on-orbit, prior to venting of ammonia from the radiator flowpath in 2017 as shown in Figure 8.

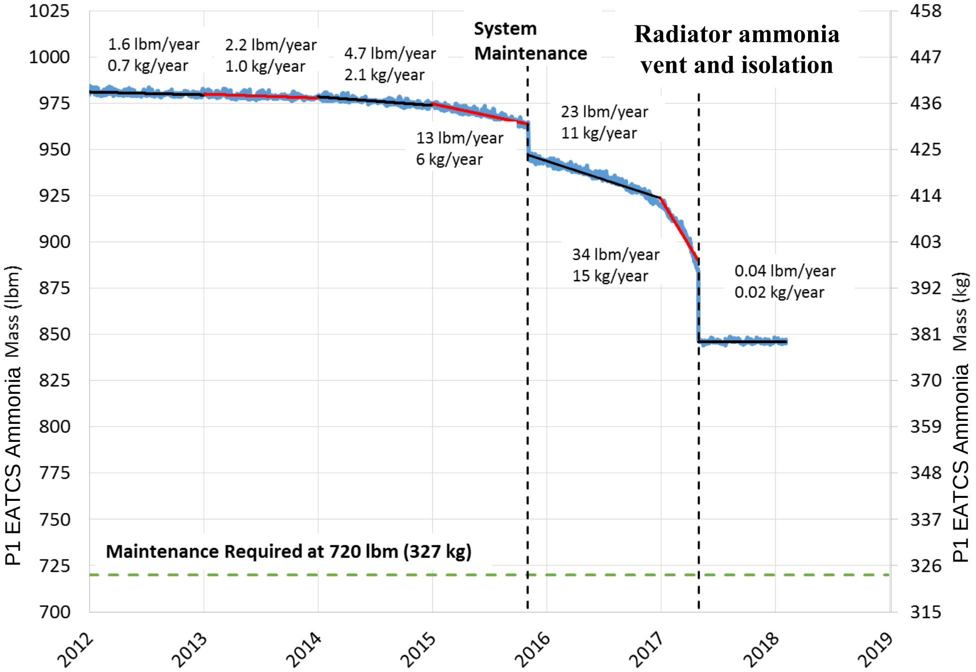

Figure 8. P1 EATCS Calculated Ammonia Mass and leak rates from 2012 to 2018.

V. Conclusions

A Technical Interchange Meeting (TIM) was held with technical experts across the agency and contractors to review all the findings from the investigation, and it was concluded that there were multiple contributors to the QD leak. The most probable root cause hypothesis is as follows:

1. The primary and secondary aft seals of QD F128 were possibly damaged during original installation, and potentially the primary seal may never have sealed properly. The secondary seal may have sealed acceptably during the first five years of service, but later began to degrade.

2. Over time and with thermal cycling, an area of Nedox plating very near or under the secondary aft seal of QD F128 failed and became delaminated, probably beginning with a small crack in the coating.

3. Because the primary seal was already compromised and an area of plating defect was near and just under part of the secondary aft seal of QD F128, leak rates measured began to increase

4. As additional thermal cycles occurred every orbit which creates micro-oscillation at the contact interface, the ability of the seal to accommodate the defect and perform well diminished over time, resulting in an increasing leak rate.

At the completion of this investigation, it was also concluded that this issue was likely unique to one QD. Even though possible Nedox adhesion issues may exist on all the EATCS radiator return jumper QDs, having a damaged seal during initial assembly and Nedox plating delamination coinciding at the seal interface is thought to be less likely to occur on all the other QDs. In addition, all the other radiator jumper QDs that are on-orbit have been in service for over fifteen years, and no other accelerating leaks have been detected on the S1 or P1 EATCS.

VI. Recommendations

At the completion of this investigation, the following recommendations were made:

1. Continue with the current sparing posture of the ISS radiators jumpers, which is to assemble and launch new jumpers as needed.
2. Install the refurbished radiator jumpers, monitor for ammonia leaks, and perform corrective actions if necessary.
3. Continue using the current QD design with the adjusted Nedox plating process for future QDs.

VII. Observations

Following the conclusion of this investigation, telemetry from the S1 EATCS (as opposed to the P1 EATCS) began showing signs of a second possible accelerating ammonia leak. Similar Robotic External Leak Locator (RELL) surveys were performed, and the results indicated that ammonia was originating from a similar radiator return jumper QD as the leaky QD F128. Further investigation is necessary to determine if the root cause is the same as QD F128 or not, and the conclusions in this paper may have to be revisited. At this time (2022), the rate of acceleration is significantly less that experienced on the P1 cooling loop and therefore the system continues to operate normally. Rapid acceleration of leak rate has not yet occurred.

Acknowledgments

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