

Extravehicular Mobility Unit (EMU) / International Space Station (ISS) Coolant Loop Failure and Recovery

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ABSTRACT

Following the Columbia accident, the Extravehicular Mobility Units (EMU) onboard ISS were unused for several months. Upon startup, the units experienced a failure in the coolant system. This failure resulted in the loss of Extravehicular Activity (EVA) capability from the US segment of ISS. With limited on-orbit evidence, a team of chemists, engineers, metallurgists, and microbiologists were able to identify the cause of the failure and develop recovery hardware and procedures. As a result of this work, the ISS crew regained the capability to perform EVAs from the US segment of the ISS Figure 1.

INTRODUCTION

The EMUs coolant system circulates water used to reject heat from the crewmember and the equipment. See Figure 2 for the Airlock/EMU Coolant Loop Schematic. During EVA, the EMU depends on vacuum for sublimation cooling. During EVA preparations, the Airlock coolant loop provides cooling for the EMU when it is at ambient pressures during EVA preparation. The Airlock coolant loop contains a heat exchanger and

umbilicals to connect to the EMU. The EMU contains the pump and systems to circulate and degas the coolant loop along with the liquid cooling garment to provide cooling to the suited crew member



FIGURE 1
– EMU
work on
orbit

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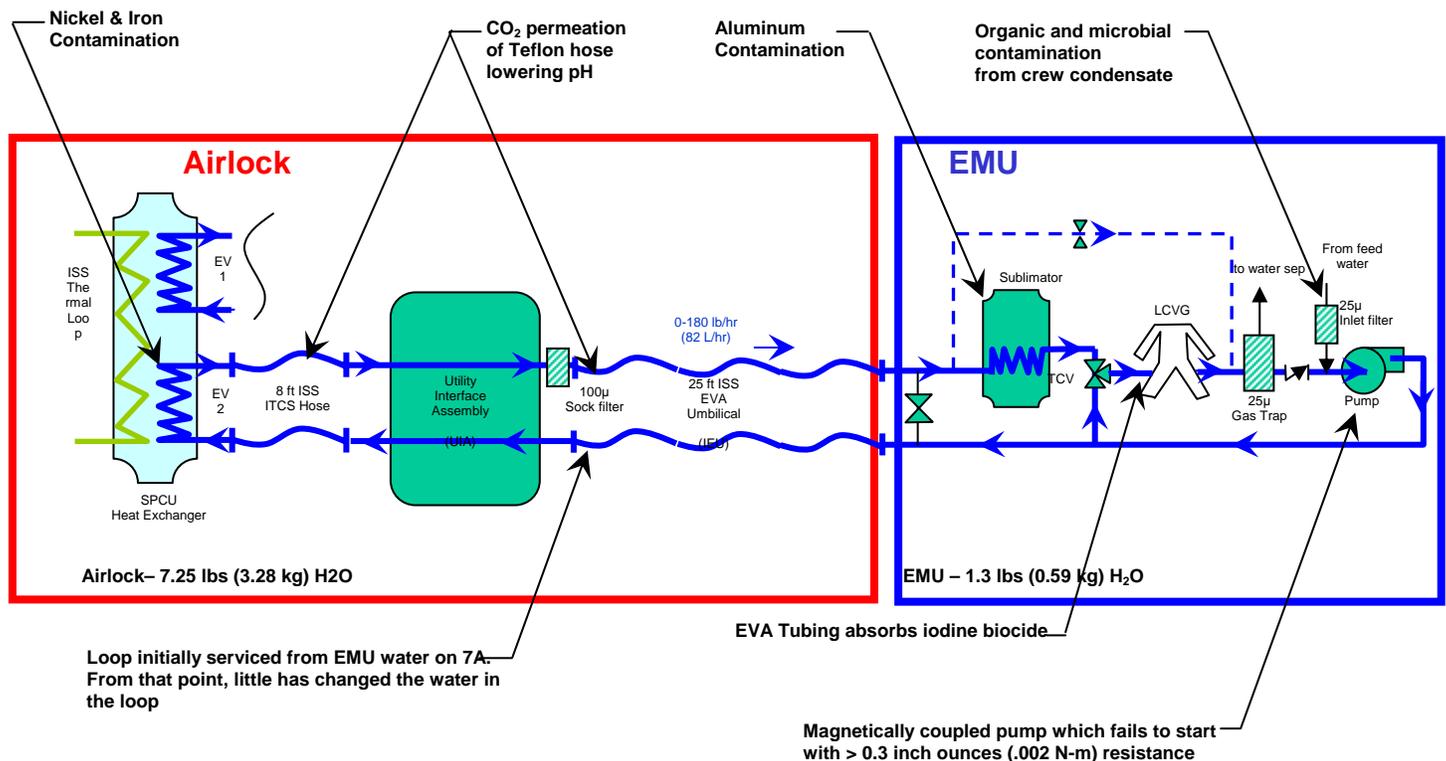


FIGURE 2 - COOLANT LOOP SCHEMATIC

DESCRIPTION OF FAILURE EVENTS

Three EMU's were onboard ISS for an extended duration following the Columbia accident. All three units eventually experienced a cooling failure. The first occurrence was on May 28, 2003. During a routine Don/Doff procedure EMU s/n 3013 failed to provide sufficient crewmember cooling. On August 7, 2003 the second EMU, s/n 3005, experienced a temporary loss of cooling that was recovered by cycling system valves. On May 19, 2004 during another Don/Doff s/n 3005 again failed to provide cooling and could not be recovered as it had been previously. During that same Don/Doff, the third EMU, s/n 3011 experienced a temporary loss of cooling but this unit was recovered by cycling system valves.

The leading theory for the loss of cooling was that the water pump rotor within the EMU cooling loop was jammed. The pump assembly is an intricate, precision device which up until this time had only been serviced on the ground. On orbit maintenance procedures were developed and spare parts were launched on a Russian vehicle. In a first of its kind on-orbit operation, the pump of EMU s/n 3013 was disassembled, cleaned and reassembled with a new rotor. The process went smoothly and cooling was successfully restored. Also a new gas trap filter was installed on s/n 3013. A small water sample and old gas trap filter from s/n 3013 were returned to Earth on Soyuz flight 6S in April of 2003. Next work on orbit was done on s/n 3005 to regain

functionality of that unit. The failed pump rotors from s/n 3013 and s/n 3005, the gas trap filter from s/n 3005, a large water sample, and some wipes used in the repair of the EMUs were returned on Soyuz flight 8S in April of 2004 for analysis.

Due to cargo constraints, only two of the three EMU's, s/n 3005 and s/n 3011 were returned on STS 114 in August of 2005. Up to this point s/n 3011 had experienced temporary cooling problems but had not failed completely. Following their return s/n 3011 was ground tested to verify it was still working at which time it failed to provide cooling, and it could not be recovered.

All three EMU's failed in a similar manner. From the time of the first units failure, extensive troubleshooting was performed both on-orbit and on the ground. The next step was to determine what had caused the rotors to jam. A team was formed to investigate coolant contamination as the primary cause of the failure. The team was led by NASA and comprised of individuals from Boeing, Hamilton Sundstrand, and Wyle Labs with expertise in chemistry, engineering, metallurgy and microbiology.

EVIDENCE FROM RETURNED SAMPLES AND HARDWARE

Coolant Water

Chemical Analysis - Samples of coolant water were collected from EMUs s/n 3005, s/n 3013, and s/n 3011 for chemical analyses. All three of these units experienced coolant flow failures; 3005 and 3013 failed on-orbit, and 3011 failed following its return to the ground. Coolant water samples were collected from three different locations within the EMU coolant loop; the Item-141 Gas Trap (3005 and 3013), the Item 123 Pump Rotor assembly (3005), and the EMU Transport Loop (TL) (3011). The coolant samples were split and aliquots were analyzed by the Boeing Huntsville Laboratory, Wyle Laboratories Water and Food Analytical Laboratory, and Hamilton Sundstrand Windsor Locks.

significant quantities of nickel (up to 5.18 mg/L), silicon (up to 15.6 mg/L), chrome (up to 1.82 mg/L), manganese (up to 3.33 mg/L), and to a lesser extent iron (up to 0.153 mg/L). This data is summarized in Table 1. Potential sources for these contaminants were determined to be the Airlock SPCU Heat Exchanger BNi3 braze alloy and the many CRES steel surfaces (Valve Module, plumbing, various valves, tubing) within the EMU Transport Loop, and the Airlock SPCU Heat Exchanger (parting sheets, headers and plumbing). In the appropriate size range, precipitates of these metals have the potential to cause the fouling of filters, as well as a decoupling of the Item-123 Pump Rotor if formed or lodged between the Rotor and Rotor Cup.

Parameter*	3005 Gas Trap Residual Water	3013 Gas Trap Residual Water	3011 Transport Loop Water	3005 Pump Housing Disassembly Water
pH	-	-	7.80	-
Conductivity (micromho)	-	-	41	-
TOC (mg/L)	57.000	48.5	21.2	-
TIC (mg/L)	16.300	29.6	4.41	-
TC (mg/L)	73.000	78.1	17.09	-
Al (mg/L)	0.139	-	0.018	0.021 (0.022)
Ba (mg/L)	0.086	-	0.007	-
Ca (mg/L)	-	2.18	-	-
Co (mg/L)	0.044	-	<0.001	2.580 (2.340)
Cr (mg/L)	1.820	-	0.020	<0.020
Cu (mg/L)	0.125	-	0.012	0.011 (0.023)
Fe (mg/L)	0.153	-	<0.005	0.100
Mg (mg/L)	-	0.49	-	-
Mn (mg/L)	3.330	-	0.038	0.067 (0.064)
Ni (mg/L)	1.400	5.18	5.440	6.700 (6.090)
Si (mg/L)	15.600	-	-	20.500
Ag (mg/L)	0.100	-	0.004	-
Zn (mg/L)	0.076	-	0.058	0.161 (0.148)
Na (mg/L)	-	18.18	0.980	-
NH ₄ (mg/L)	-	2.95	1.44	-
K (mg/L)	-	5.62	0.32	-
F (mg/L)	-	0.59	<0.1	-
Cl (mg/L)	-	8.52	0.35	-
NO ₃ (mg/L)	-	1.90	<0.11	-
NO ₂ (mg/L)	-	0.16	<0.08	-
FTIR (qualitative)	-	-	<ul style="list-style-type: none"> • Butylbenzenesulfonamide • Bis-2-Ethylhexyl phthalate • Zyglo ZL-67 (C12 - C18 mix of alcohols) 	-

Residual water drained from the Item-141 Gas Traps that were removed from EMUs 3005 and 3013 contained

TABLE 1: EMU- ISS Flight 8S Water Sample Chemical Analysis Results

* Metals reported as total only (dissolved in parentheses where appropriate)

The chemical analysis of the Item-141 Gas Trap residual water samples also indicated the presence of high levels of total organic carbon (TOC). The samples from s/n 3005 contained 57.0 mg/L TOC and the sample from s/n 3013 contained 48.5 mg/L TOC. Two potential sources of the TOC load were identified as astronaut respiration and material leaching. The air exhaled by the crew member in the EMU is condensed in the Item-140 Sublimator and returned to the cooling water loop. This creates a pathway for organics to enter the cooling loop. The other potential source of TOC is leaching of extractable compounds from nonmetallic materials used in the Transport Loop (TL). TOC at the measured levels in these samples represents a potential nutrient source for microorganisms and can collect on surfaces depending on the solubility of the organic compounds. Both of these scenarios (microbial bloom and organic film formation) can exasperate the precipitation of metal salts and lead to a failure in the coolant loop.

The chemical analysis of the TL / ISS Water Circuit coolant water sample collected from EMU 3011 is summarized in Table 1. As mentioned previously, EMU s/n 3011 had not experienced a coolant flow failure at the time of sample collection; it did so following return to ground. However, this unit provided a good source of coolant water that had an significant dwell time in the EMU comparable to the flow compromised EMU 3013. The larger volume would allow for more in-depth analysis. From an inorganic and organic load perspective, the EMU 3011 coolant water was very similar to that drawn from EMU 3013 in September of 2003. (1) Of particular interest are the compounds that make up the organic load in the EMU 3011 water. For the most part, the EMU 3011 organic load appeared to be non-volatile in nature (Non Volatile Residue (NVR) = 42.8 mg/L and largely organic based on Fourier Transform Infrared (FTIR) analysis). Positively identified organic compounds included N-butylbenzenesulfonamide (a common rubber plasticizer), bis-2-ethylhexyl phthalate (a plasticizer commonly used in Tygon tubing), and Zygo ZL-67 (a weld/braze check dye penetrant mixture of mineral oil and C12 – C18 alcohols used at Hamilton Sundstrand/Windsor Locks).

The FTIR spectrum also showed evidence of protein-like compounds, verified by hydrolysis of the material

followed by amino acid analysis using o-phthaldehyde derivitization with high performance liquid chromatography (HPLC) utilizing fluorescence detection. Previous EMU TL water samples have shown evidence indicating the presence of non-ionic surfactant type compounds in the coolant water. The presence of high levels of non-volatile organic compounds, such as non-ionic surfactants, in concert with precipitated metals can yield a particularly tenacious precipitate. Precipitates of this character have the ability to trap contaminants as they flow by, which can add to previously collected deposits.

The chemical analyses of the water collected from the Item-123 Pump Rotor assembly from EMU 3005 focused on metals analysis due to the limited sample size. The data, listed in Table 1, showed significant concentrations of nickel (6.7 mg/L) and silicon (20.5 mg/L). The presence of these metals is consistent with findings from the other coolant water samples. Unlike the other samples, the Item-123 Pump Assembly water also contained a significant quantity of cobalt (2.34 mg/L). The most likely source for the cobalt contamination was determined to be the cobalt/samarium magnet in the Item-123 Pump Rotor assembly.

Microbial Analysis - Microbial counts in the water coolant removed from the EMU 3005 Gas Trap were in the 10^8 CFU/ml (colony forming unit per ml) range, which is considered to be highly contaminated. The EMU 3011 Transport Loop coolant water showed microbial counts of about 10^6 CFU/ml, considered to be moderately high. Data collected during the microbial analyses of the coolant water samples are summarized in Table 2. The current ISS specification for microbial counts in US supplied potable and technical water is 50 CFU/mL (3). For the most part, the identified microorganisms were commonly encountered water-borne species known to form biofilms in water systems (Ralstonia - previously included in the Pseudomonas genus). Microorganisms of this type and in the quantities detected can lead to biological fouling of filters, gas traps, and other fine orifices. The formation of biofilms can exasperate issues caused by the formation of inorganic precipitates in a water system, and vice-versa.

Finding	EMU 3005 Gas Trap Residual Water	EMU 3005 Gas Trap Bag Swab	EMU 3011 Transport Loop Coolant Water Boeing/Huntsville	EMU 3011 Transport Loop Coolant Water Wyle/Houston
Total Count (CFU/cm ²) CFU = colony forming unit	-	1.68 x 10 ⁻³	-	-
Total Count (CFU/ml)	4.71 x 10 ⁸ 1.38 x 10 ⁸	-	3.30 x 10 ⁶ 3.30 x 10 ⁶ 1.10 x 10 ⁶ 1.10 x 10 ⁶	1.50 x 10 ⁴ (at 48-hours)
Predominant Genus/Species Observed	<ul style="list-style-type: none"> ▪ Ralstonia pickettii ▪ Rakstonia eutropha 	<ul style="list-style-type: none"> ▪ Ralstonia pickettii ▪ Rakstonia eutropha 	<ul style="list-style-type: none"> ▪ Unidentified non-fermenting gram negative rod ▪ Sphingomonas species ▪ Ralstonia pickettii ▪ Sinorhizobium meliloti 	<ul style="list-style-type: none"> ▪ Ralstonia pickettii ▪ Sphingomonas species ▪ Sphingomonas stygialis ▪ Methylobacterium Podarium

TABLE 2: EMU-ISS Flight 8S Water Sample Microbial Analysis Results

Hardware

Item-141 Gas Trap - The EMU 3013 Item-141 Gas Trap influent and effluent surface high magnification images (Figure 3) showed the presence of significant agglomerations of organic material mixed with inorganic precipitates (nickel, silicon and aluminum), a number of which exceeded 100-microns in size. It is important to note that these agglomerations appeared to be made up of particulates that were significantly less than the 20-micron screen rating of the Gas Trap, but when joined together as agglomerations, exceeded 100-microns in size. Importantly, these agglomerations were in a size range that could cause a decoupling of the Item-123 Pump Rotor if they became dislodged, then re-deposited between the Item-141 Rotor and Rotor Cup. (1)

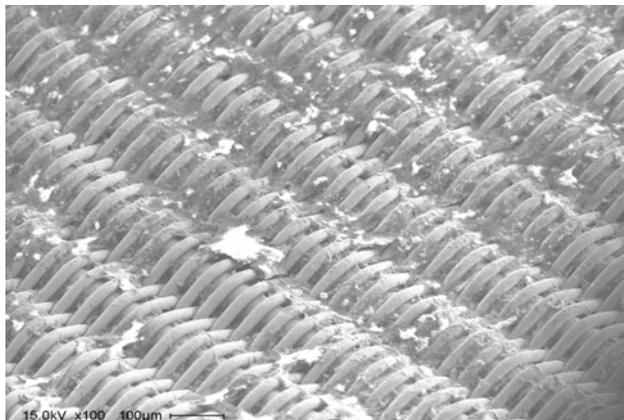
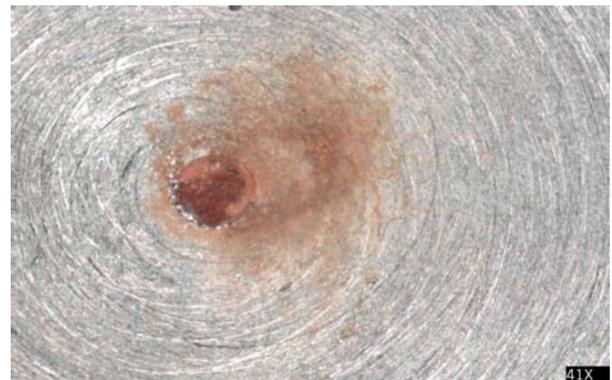


FIGURE 3: Outer Surface of EMU 3013 Gas Trap (100X)

The EMU 3005 Item-141 Gas Trap was not functioning on-orbit. In that respect, the failure signature of EMU 3005 and EMU 3013 diverged. It was determined through examination that the center 0.155 in. diameter hole in the Gas Trap Cover of the EMU 3005 Item-141 Gas Trap was completely plugged. This prevented flow of water to the Water Separator. The contaminant blocking this hole was identified as primarily iron oxide,



with lesser amounts of non-volatile organic material. (Figure 4)

FIGURE 4: EMU 3005 Item-141 Gas Trap Cover Blocked Hole

Orange/brown contamination was observed on the Inner diameter (ID) (influent side) and outer diameter (OD) (effluent side) of the EMU 3005 Gas Trap screen and housing as well, and was identified as primarily iron corrosion products dispersed in non-volatile organic material. The coloration of this residue was in stark contrast to the greenish/brown residue observed in the EMU 3013 Item-141 Gas Trap one year earlier. The inorganic contaminants observed in the EMU 3013 Item-141 Gas Trap contained a higher percentage of nickel corrosion products, with lesser quantities of iron. (1)

The OD screen material of the EMU 3005 Item-141 Gas Trap appeared to be covered with a clear, wet gelatinous material initially thought to be moisture. A higher magnification examination of this material revealed "stringers" that bridged the gap between the OD screen convolutions. A microbial count and speciation of this material collected on swabs, and the finding of high levels of protein, indicated the presence of biofilm and biofilm forming microorganisms. This is similar to what was observed with the EMU 3013 Gas Trap as well. (Figure 5)



FIGURE 5: EMU 3013 Gas Trap OD (~ 40X)

The ID and OD high magnification examinations of the EMU 3005 Item-141 Gas Trap screen material yielded results similar to what was observed a year earlier with the EMU 3013 Item-141 Gas Trap. (1) Specifically, the ID screen surfaces appeared to be cleaner and appeared to have retained contaminants by size exclusion. The OD screen surfaces appeared to be more contaminated, and the contaminants appeared to be extrusions that had agglomerated thereafter.

Of particular interest is the fact that the inorganic character of the contaminants observed in the EMU

3005 and EMU 3013 Item-141 Gas Traps was significantly different (high iron in the former, high nickel in the latter) (Ref. 1). The organic character however (indications of non-volatiles, which resemble biofilm material) was quite similar. With the differences and similarities in mind, the end result of contaminants extruding through the Gas Trap screen material to the OD (effluent surface), and agglomeration thereafter were almost identical. Both collections of agglomerations on the OD (effluent) surfaces of the Item-141 Gas Traps represented debris that if dislodged and or re-deposited downstream, could have adversely impact the performance of the downstream Item-123 Fan/Pump/Separator Pump Impeller Rotor.

An FTIR microscope examination of select particles from the EMU 3005 Item-141 Gas Trap was conducted at Boeing/Huntsville. Spectral matches include a urea-formaldehyde condensation product with cellulose (several particles), Krytox, aluminum nitrate nonahydrate, PTFE, natural cotton, alpha cellulose, an epoxy compound, a methyl ester of abietic acid, silica and a non-ionic surfactant. Numerous cellulose-like material particles and contaminants observed on the EMU 3005 Item-141 Gas Trap were considered to be indications of the presence of biological biofilm. The presence of Krytox and other fluorocarbon compounds were observed as well, and were not unexpected since Krytox is common fluorocarbon grease used in numerous areas of the EMU Transport Loop. The presence of an epoxy compound was not considered unusual either, since there are many epoxy compounds used in the both of the EMU water loops (PD George epoxy coating, BR-127 epoxy coating, constituents of the Hard Upper Torso (HUT) tube walls, etc.). The finding of a methyl ester of abietic acid could conceivably be linked to the prior use of Neoprene Bladders in the Feedwater Loop. The presence of silicon and aluminum salts was again, indicative of corrosion products from the Internal Active Thermal Control Subsystem (ATCS) Airlock Heat Exchanger braze alloy and other EMU water loop materials of construction. (1) (2)

An FTIR microscope examination of select particles from the EMU 3005 Item-141 Gas Trap was conducted at Boeing/Huntsville. Spectral matches included a urea-formaldehyde condensation product with cellulose (several particles), Krytox, aluminum nitrate nonahydrate, PTFE, natural cotton, alpha cellulose, an epoxy compound, silica and a non-ionic surfactant. The non-ionic surfactant was tentatively identified as a polyethylene glycol ester of a long chain fatty acid using a FTIR microscope. The tentative identification was confirmed by hydrolysis of the material, and confirmation of the resultant C-16 fatty acid by Gas Chromatograph/Mass Spectrometer (GC/MS).

Item-123 Fan/Pump/Separator Pump Impeller Rotor -

The initial examination of the EMU 3013 Pump Impeller Rotor indicated that it had increased by .003-.004 inches in length. The increase in length had occurred as a result of a widening in the gap between the Nitronic -60 cap and the impeller assembly (Figure 6). The impeller appeared to have de-bonded from the corroded steel core and appeared to be lifting out of the cap. The rotor is encased within a seal cup cavity and any increase in length would be expected to make the rotor more susceptible to fouling from contaminants. The chemical analyses of the contamination on and within the EMU 3013 Item-123 was consistent with the organic contaminants and nickel, silicon and iron corrosion products previously observed in the coolant and on the Item-141 Gas Trap. Observed rust colored deposits were rich in iron and oxygen, indicating the presence of iron oxide corrosion products.

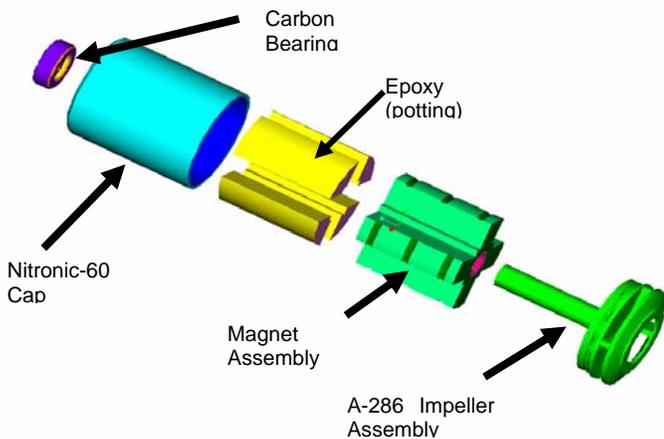


FIGURE 6: Item-123 Rotor Schematic

The EMU 3005 Item-123 Fan/Pump/Separator Pump Impeller Rotor exhibited more rust colored contamination than EMU 3013. This rotor showed a growth in length of approximately 0.005 inches. (Figure 7) This is slightly greater than the 0.003-0.004 inches growth seen in EMU 3013. Again, since the rotor is incased within a seal cup cavity, this growth in length would be expected to make the rotor more susceptible to fouling from contaminants.

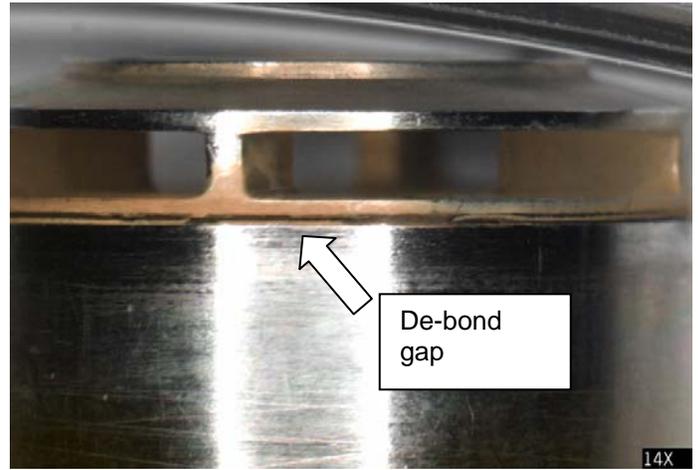


FIGURE 7: EMU 3005 Item-123 Rotor De-bond Gap

Because the EMU 3005 rotor displayed the more pronounced case of de-bonding and contamination, it was selected for further examination. The rotor was cross-sectioned in an attempt to gain information on the condition of the bond joints within the rotor. The impeller shaft appeared to have de-bonded from the cold rolled steel core. The epoxy bond to the cap remained intact. The growth in rotor length was attributed to the de-bonding of the Impeller. The Impeller was no longer seated in the cap and had risen out of the cap slightly.

The EMU 3011 rotor exhibited no growth in length in the gap between the Nitronic-60 cap and impeller assembly (Figure 6). No evidence of de-bonding was observed. It is theorized that the increased gap between the Nitronic-60 cap and the impeller assembly for the EMU 3005 and 3013 Item-123 rotors are the reasons this hardware experienced coolant flow disruptions before EMU 3011. It should be noted that the occurrence of a rotor growth in length is not necessary for an eventual disruption of Item-123 rotor functionality. Coolant quality remains as the primary reason for EMU coolant flow disruption, and rotor growth a significant other finding.

Hardware Surface Wipes - Examination of the various wipes used on the EMU 3013 and 3005 Item-123 yielded no "smoking-gun" with respect to what may have caused the cooling loop failures in the two systems. Findings were such that observed contaminants could have been responsible for the binding of the Item-123 Rotor, had they been deposited in a low-tolerance area. The wipe operation was "after-the-fact" in that any contaminant observed on a wipe had already been dislodged from the Rotor and Rotor Cup surfaces during disassembly.

The contaminants on wipes used for the EMU 3005 Item-123 Rotor clean up yielded significantly more observable contaminants, primarily iron corrosion products. The EMU 3013 wipes exhibited contaminant

elemental ratios more indicative of the Nitronic-60 Item-123 Pump alloy. The character of the inorganic contaminants varied between the two assemblies as was observed with the two Item-141 Gas Trap screen deposits.

A number of non-volatile organic compounds were extracted from the wipes. Potential sources of observed organic acids include residual cleaner used in earlier hardware cleaning or human metabolic byproducts found in perspiration. A bis-ethylhexyl phthalate compound that was observed is used as a non-metallic plasticizer commonly found in Tygon tubing. The source of a Colest-5-en-ol (3-beta) compound may be related to biofilm material or human metabolic byproducts found in perspiration.

Item-127 Pump Inlet Filter - The Item-127 Pump Inlet Filter from EMU 3013 was found to be relatively clean, when compared to the Transport Water Loop components examined from EMU 3013 and 3005. The cleanliness of this filter was not unexpected since the water sources it was exposed to were the initial ground water, water storage in the ISS Teflon water storage bag, and water stored in the EMU Fluorel bladders.

SEM/EDS analysis of the small amount of observed residue indicated the presence of unidentified organic compounds. Identification could not be accomplished due to the limited amount of sample. Microbial biofilm was suspected due to the fact that prior analyses of EMU Fluorel water has shown the presence of moderate levels of microorganisms and no active iodine biocide. The presence of silicon may be due to silicates in the initial charge water from the ground. Silicates have been found in the ground water charged into the EMU in prior investigations.

The presence of fluorocarbon in the SEM/EDS data indicated the potential of Krytox being present. This was confirmed by Freon 113 solvent extraction / FTIR analysis. Methanol solvent extraction / FTIR data also suggested the presence of Nylon extract. This is an indication that the water charged into the EMU Fluorel bladders had previously been in contact with Nylon, a material not recommended for use with the EMU water.

ORBIT RECOVERY

From the analysis done on the returned EMU hardware, an approach was developed to maintain the on-orbit system. The approach uses a filtration system that is installed in the EMU where the liquid cooling and ventilation garment is connected. The filtration system includes a particulate filter for biomass or salt particulates, a mixed bed ion exchange resin and charcoal to absorb the metal ions. The filtration system is installed in the EMU before and after EVA operations to maintain the loop coolant quality and to clean the

EMU coolant water before storage. If the EMUs are to be stored for over 90 days, they are re-cleaned. Development and operation criteria for the filtration system are described in ICES paper 2006-01-2096.

GROUND SYSTEMS RECOVERY

The team investigated nominal ground processing procedures for the EMU's with respect to the cooling loop. Other than sampling of the coolant, it was found that activity related to the cooling loop was minimal post-flight and post-manned chamber run. This is a critical time for the cooling loop because manned use of the EMU results in the introduction of organic contaminants from the crewmember. The water cooling circuit interfaces with the human metabolic loop in the EMU. This causes organic contaminants to be introduced into the water cooling circuit. The organic contaminants provide food for biomass growth and if left unchecked could pose a significant threat to critical components within the loop. Flushing and or polishing of the cooling loop fluid after manned use and recharging with iodinated water would be of significant benefit to the overall health of the cooling loop and its critical components. These changes are currently being implemented as part of the overall recovery plan.

Unlike EMU s/n 3013, EMU s/n 3005 was never verified on-orbit after the repair. 3005 and 3011 were ground tested immediately upon return. 3005 ran, passed all leak checks and performed nominally. This was a more rigorous set of tests than 3013 had undergone on-orbit and provided additional confidence as to the efficacy of the repair. 3011 experienced intermittent coolant problems on-orbit but had provided cooling during the last check out. 3011 failed to provide cooling flow in ground testing and cooling could not be recovered as it had on-orbit.

Both EMU's were sent to Hamilton Sundstrand, in Windsor Locks Connecticut for further evaluation and teardown. 3011 was the first unit to be worked. Water samples from the cooling loop were taken and analyzed. The EMU was then disassembled to the component level for evaluation and inspection. Varying levels of contamination were found within the cooling loop. The component hardware and contaminants were thoroughly evaluated by a team of metallurgists, chemists and microbiologists. Identifying the contaminants was critical to the recovery of the hardware. In order to return the hardware to a flight ready condition, the contaminants had to be thoroughly removed and cleanliness verified. Cleaning trials were conducted using standard cleaning procedures but they proved to be inadequate to remove all contaminants. Further work would be needed in order to develop effective cleaning processes for this hardware. At the time of the writing of this paper, that effort is underway.

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KEYWORDS

Extravehicular Mobility Unit, International Space Station, Thermal Control Subsystem, Extravehicular Activity