Gas Trap Plug Design, Function and Performance

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The cooling loops of the Internal Active Thermal Control System (IATCS) on the Node 3, Node 2 and US Laboratory (USL) Modules of the International Space Station (ISS) have been serviced by Gas Traps (GTs) since the onset of operations. These traps serve to protect the pumping function of the cooling loops by eliminating free gas that would otherwise impact the impellers and cause a loop shutdown. Gas Trap Plug Assemblies (GTPAs) have been designed, manufactured and tested, to permit function of the IATCS in the event of a loss of cabin atmosphere and long term decrew event. The GTPA also serve to give the crew additional time to evacuate the United States Operating Segment (USOS) in the unlikely event of an Ammonia breach of an Interface Heat Exchanger (IFHX). These GTPAs have been installed on the ISS IATCS since May 2019. This paper will address purpose, design and testing of the GTPA. The paper will also provide analyses showing residual trapping capability and free gas elimination of the GTs even while tightly plugged, for both the GTs and the Alternate Gas Trap Assemblies (AGTAs) ground spares.

Nomenclature

AGTA	=	Alternate Gas Trap Assemblies
COL	=	Columbus Module
EATCS	=	External Active Thermal Control System
GT	=	Gas Traps
GTPA	=	Gas Trap Plug Assembly
IATCS	=	Internal Active Thermal Control System
IFHX	=	Interface Heat Exchanger
JEM	=	Japanese Excursion Module
LCA	=	Loop Crossover Assembly
LTL	=	Low Temperature Loop
MTL	=	Moderate Temperature Loop
ORU	=	Orbital Replacement Unit
PPA	=	Pump Package Assembly
PTFE	=	Polytetrafluoroethylene
USL	=	US Laboratory
USOS	=	United States Operating Segment

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I. Introduction

THE GTs are an integral ORU (Orbital Replacement Unit) of the Pump Package Assembly (PPA). USOS of the ISS has been continuously operating with GTs since February 2001 (see Figure 1). These GTs protect the pump from a rapid infusion of gas that could cause the pump to overspeed and shut down the cooling loop. In the worst case the GTs prevent gas bubbles with a diameter greater than 0.0254 m (1 inch) from potentially vapor locking the PPA impeller, a condition that is difficult to recover from operationally. There are a total of six GT ORUs in operation, one for each of the Low Temperature Loop (LTL) and Moderate Temperature Loop (MTL) of the Node 2, Node 3 and USL modules on ISS. Typically the USL module operates in single loop mode with LTL PPA providing flow to both the LTL and the MTL through a Loop Crossover Assembly (LCA). Node 3 also has the LCA capability, but typically operates in Dual Loop mode. This means that five of the six in-line GTs are essentially continuously operating. The Japanese Experiment Module (JEM) and the Columbus Module (COL) each have a similar gas trap capability, but these are typically only employed when a new payload is added to the system.

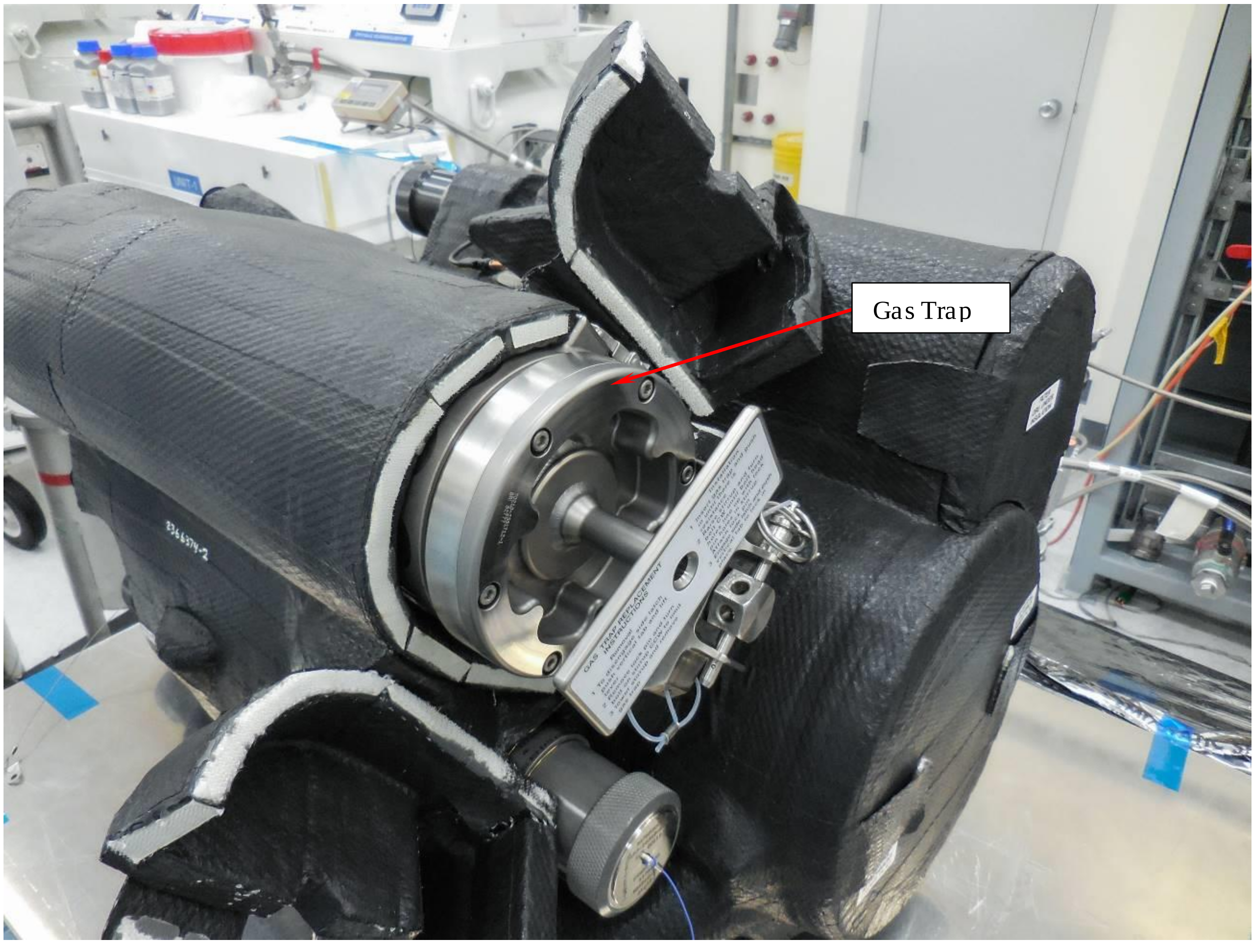

Figure 1. Pump Package Assembly with Gas Trap (with insulation cover open).

The GT is upstream of the pump, but is also upstream of the PPA accumulator to prevent it from ingesting free gas, see Figure 2. A 2 μm Filter ORU is situated just upstream of the GT protect it from fine debris that would otherwise plug the GT pores. The GT has a one-way check valve that will open passively as the pressure across it reaches 42.75 kPa to 48.27 kPa (6.2 psid to 7.0 psid). This condition occurs if the GT becomes transiently overfilled with gas. The pressure drop across the GT is monitored by a differential pressure transducer that allows operators to assess system GT function. The upstream filter is also similarly equipped with a bypass leg with a passive check valve and a differential pressure transducer.

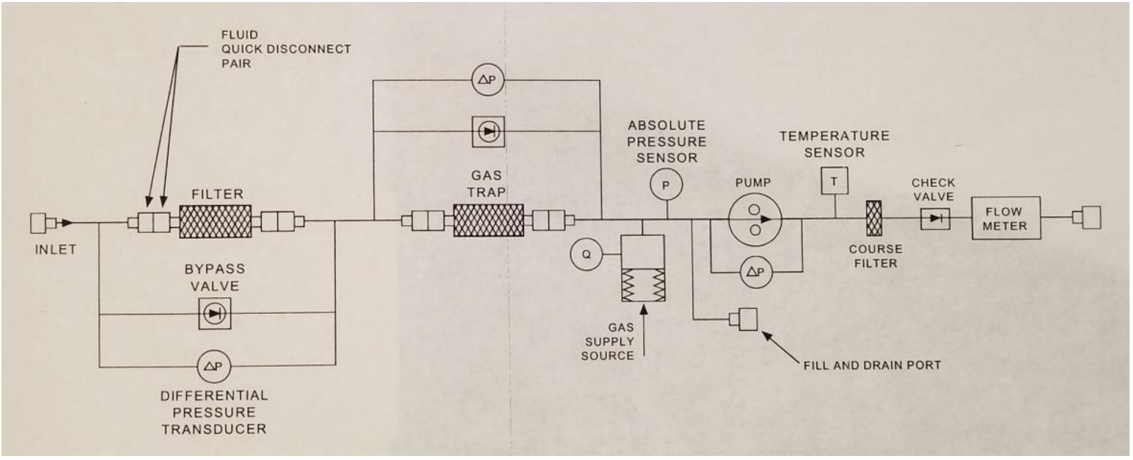

Figure 2. Pump Package Assembly Functional Diagram

A. Features of the Gas Trap (GT) and Alternate Gas Trap Assembly (AGTA)

The GT currently operate on all the USL, Node 2 and Node 3 modules. The GT consists of 84 tube sets, each containing an outer tube and and inner tube, see Figure 3. The IATCS coolant, that is 99.3% by weight water, enters the GT through the inlet header and into 84 tube sets in the annular spaces between the outer and inner tubes. The outer tube is micro-porous and hydrophilic, allowing the coolant to pass freely across the tube wall to exit the trap at the GT outlet, but retaining any of the entrained free gas. The inner tube is micro-porous and hydrophobic, restricting the coolant from leaking into the vent space while allowing the entrained free gas to pass through the inner tube wall driven by the higher coolant pressure into the ambient pressure inside the inner tube and then flows out the tube into the vent space.

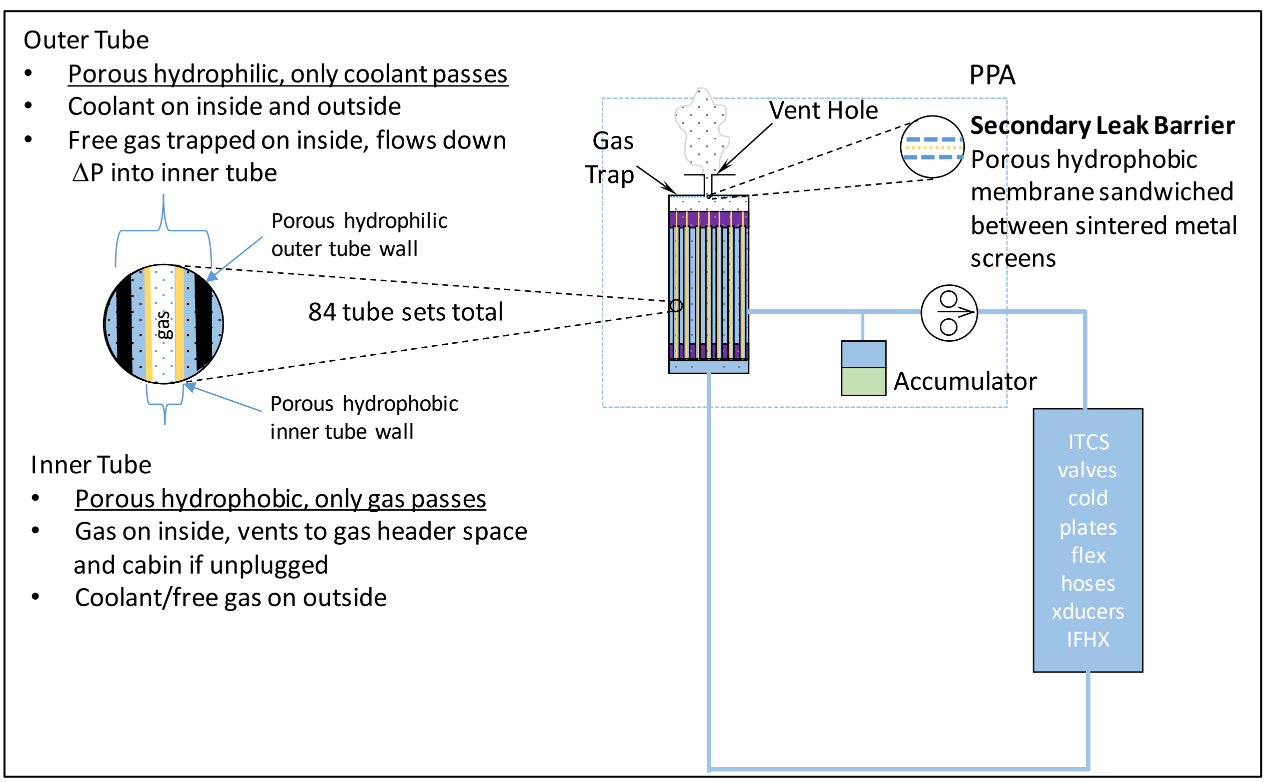

Figure 3. Features of the GT Design

The ATGA is built without the micro-porous hydrophilbic outer tubes. Instead, it is constructed of the same porous hydrophobic tubes as the inner tubes of the GT. But there are more than 15,000 tubes tightly spaced in a multilayer spiral wrap around a hollow inner core. The coolant flows into the inlet header and then into the inner core. The coolant then passes radially out of the core between the spaces of the hydrophobic tubes and exit the system. Any entrained free gas is swept radially outward by the coolant flow where the air bubbles make contact with the hydrophobic tubes, and driven by the higher pressure of coolant, the air flows through the pores into the ambient pressure tubes and out into the vent space. Because of the high number of tubes, the AGTA can eliminate gas from the system more quickly than the GT, but both ORUs meet the PPA specification for elimination of free gas: "With continuous inlet conditions of equal to or less than 3.2 pct (by volume) of air at 144.8 kPa (21 psia) and a temperature of 21.11 ºC (70 ºF) at 1360.8 kg/hr (3000 lbm/hr), the PPA gas trap shall provide coolant with a noncondensed gas concentration no greater than 0.5 pct (by volume)."[1]

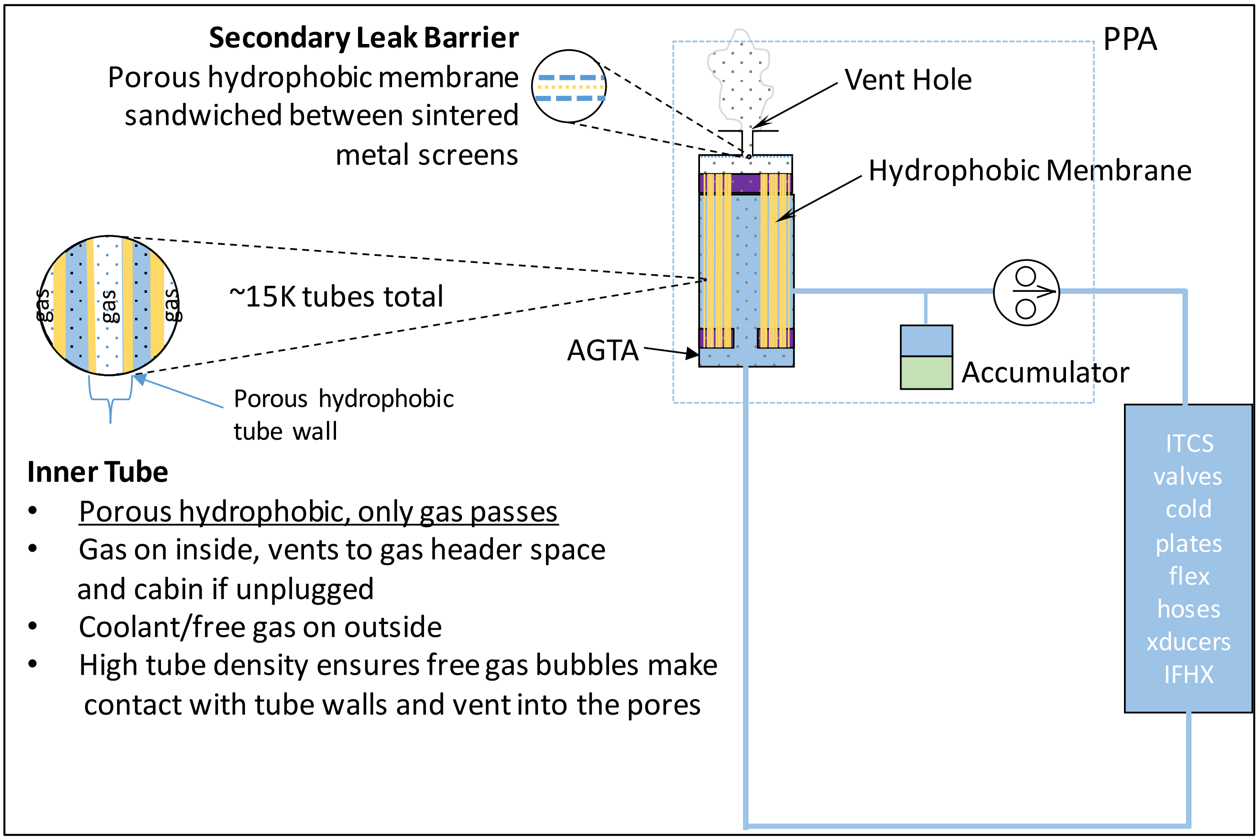

Figure 4. Features of the AGTA Design

B. The Need For Gas Trap Plug Assemblies (GTPAs)

While the risk of crew evacuation due to an ammonia breach from the External Active Thermal Control System (EATCS) into the IATCS through the IFHX is only 1 in 14,000 over a six month period, the consequences are catastrophic.[2] This failure puts the crew itself at risk. The IATCS of both the JEM and COL modules have the physical capability of holding pressure against such a breach, but not the USOS modules. A study on vulnerability of IATCS components shows that the GT housing would withstand an ammonia breach.[3] If the vent port on the GT could be successfully plugged against the breach pressures, then it would not be the most vulnerable component. This study shows that the PPA bellows would then be the first to burst. The GTPAs had the potential to give the crew valuable time to don protective gear and move to a safe haven.

A far more likely cause for the crew to evacuate, with a 1 out of 170 chance in a six month period, is due to Micro Meteoroid Orbital Debris strike and loss of cabin atmosphere.[2] The GTPA would not prevent the crew from evacuating but it is critical to meet the programs goal of 180-day controlled de-orbit capability in the event of such a cabin depressurization. This would help to minimize the risk to public safety. The reason for this is that one of the two Gas Trap designs, the AGTA, in a vacuum environment would evaporate 1.85x10^{-4} kg/min (4.07x10^{-4} lbm/min) of IATCS Fluid, exhausting the accumulators in 28 days and causing a system shutdown and loss of dependent avionics.[4] The GTPAs would retire this risk.

The Boeing Company performed a feasibility study of simple plugging methods. Based on the results of this study, the ISS Program directed The Boeing Company to design, build and test the GTPAs for the USL, Node 2 and Node 3 modules.[5] This was done in collaboration with NASA as a best effort to mitigate these two serious hazards.

II. Requirements, Functional Design and Testing of GTPA

A. Requirements for GTPA

A simplified project plan was established for the development of GTPAs with the goal of expediting the implementation of the plugs on ISS without creating new hazards for the crew. This called for a limited set of requirements: 1) No modification of the GT or AGTA vent; 2) IVA installable/removable without the use of tools; 3) Able to fit within the envelope of the current USL, Node 2, and Node 3 rack or alcove, see Figure 5; 4) Operable within acceptable crew induced loads; 5) Compliance with safety requirements (via normal Safety Review Panel process); 6) Assess through analysis and/or test that the installation and certification of the gas trap plug will enable nominal IATCS operation; 7) Cause no damage or create no hazards during off nominal situation including IATCS operation during a contingency depress. The GTPAs need to be readily installed by the crew on the T-handle while the PPA is operational. These requirements imply that the GTPA must be readily deinstalled by hand as the GT and AGTA function needs to be used periodically whenever a payload is introduced into an IATCS loop, or when loop filling operations, or during antimicrobial dosing. This neccessitates that the plug be designed to be cycled for the life of the station. For this purpose 12 GTPAs (6 active and 6 spares) with 60 non-metallic plugs were required. While not a requirement, the functionality of the plug would be evaluated for leak over the range of pressures of the EATCS up to and including the maximum ammonia pressure of 3102 kPa (450 psia).

Figure 5. USL LTL PPA

B. Functional Design of the GTPA

Figure 6 shows the GTPA practical features. The GTPA has a bracket for easy insertion over the T-handle. The bracket has a slotted guide to abut the T-handle neck with the end of the guide thus aligning the GT vent hole with the center of the plug. The plug is screwed in place against the T-handle label through a large knurled knob, sized to provide a mechanical advantage for the crew. This transmits the turning torque into to a large downward force of the plug surface against the perimeter of the T-handle surrounding the vent hole. The plug is attached to


Figure 6. GTPA

the threaded driving rod through a swivel feature (not shown). This degree of freedom results in point loading of the plug by the driving rod. This ensures uniform pressure across the T-handle sealing surface, and eliminates any torque on the plug itself.

C. Testing of the GTPA

Table 1. GTPA Pressure Test Matrix

	Evaluation Cycle (EC) 1		EC 2	EC 3	EC 4	EC 5	EC 6	EC 7	EC 8	EC 9	Evaluation Cycle (EC) 10		
Evaluations Performed >>>	5 minute Dwell Leak Check	10 minute Dwell Leak Check	Ambient to 75 PSIA two minute Dwell no leak check	Ambient to 75 PSIA two minute Dwell no leak check	Ambient to 75 PSIA two minute Dwell no leak check	Ambient to 75 PSIA two minute Dwell no leak check	Ambient to 75 PSIA two minute Dwell no leak check	Ambient to 75 PSIA two minute Dwell no leak check	Ambient to 75 PSIA two minute Dwell no leak check	Ambient to 75 PSIA two minute Dwell no leak check	5 minute Dwell Leak Check	10 minute Leak Check Dwell	
75 psia	X		X	X	X	X	X	X	X	X	X		ITCS Operating range (Contingency De-orbit)
180 psia	X										X		Line where single phase occurs (EATCS)
300 psia	X										X		Typical lower operating range (EATCS)
350 psia	X[1]	X[2]									X[1]	X[2]	Range that Ammonia Scrubber project uses (EATCS)
400 psia	X[1]	X[2]									X[1]	X[2]	High range point in typical ops (EATCS)
450 psia	X[1]	X[2]									X[1]	X[2]	Bounding upper limit (EATCS)

[1]Consistent with SSP41172 recommendation for leak testing
[2]Longer dwell time requested by Ammonia Scrubber project for use in future analysis
[3]Each Evaluation Cycle (EC) includes unplugging/replugging vent hole

To address the pressure capability as a function of install/deinstall cycles, an GTPA Pressure Evaluation Matrix was devised consisting of a sequence of 10 Evaluation Cycles (ECs), see Table 1.[6] For these tests a fixture was created to mimic the mounting geometry and sealing surface of the T-handle with label. The fixture was made according to the T-handle specification and coupled to a regulated nitrogen pressure source. The first part of EC 1 is a series of incrementing pressures ranging from the IATCS operating pressure of 517 kPa (75 psia) to the bounding ammonia pressure of 3102 kPa (450 psia), each with a 5 minute dwell time. A soap bubble leak is performed for EC1. The last four pressures covers relevant EATCS ammonia operating pressures and span the EATCS range. These last three tests are repeated with a 10 minute dwell time.

Having evaluated the plugging capability up to the maximum EATCS ammonia pressure, the plug is then put through EC 2 through EC9 where in each EC the test fixture is depressed, the GTPA is removed, then reinstalled, then pressurized to the nominal operating level of 517 kPa (75 psia). Nominally, the pressure across the plug is actually close to zero, regardless, each of these cycles is done with the full installation loading, that is the prescribed ¾ turn of the knurled knob after the initial seating of the plug, as if it were to hold the maximum pressure loading of 3102 kPa (450 psia). EC 10 is a repeat of EC 1, showing that the GTPA can hold the maximum pressure after nine installation/deinstallation cycles. This is in effect a confidence test that the plugs will easily hold during a cabin depress, and would not fail before the pump accumulator that ruptures at 1993 kPa (289 psia). With a complement of 60 replaceable plug feet, each GTPA could go through 100 installation/deinstallation cycles. This will easily cover the expected life of the ISS.

III. Analysis of GT and AGTA Operation with installed GTPAs

While the confidence test shows that the GTPA will function after multiple installation/deinstallation cycles, thereby permitting intermittent venting operation of the GTs or AGTAs, this does not consider their nominal and contingency function with presence of the installed GTPAs. For this an analysis was performed that considers the impacts of plugged configuration during nominal operation, and the effects of reduced loop pressure, temperature variations and humidity.

A. Impacts on Plugging on Nominal Operation

With air as a dilute solute in the IATCS fluid (essentially water), the solubility of the air in the water is described by Henry's Law[7]:

$$H = c_a/p$$

where Henry's constant H is defined as the ratio of c_a, the concentration of gas (air) in the aqueous phase, and p, the partial pressure of the gas in equilibrium with the aqueous solution. In this case p is 1 atm. This however is somewhat complicated by the fact that the aqueous phase is at a higher pressure than the air at 1 atm. With the GTPA unplugged, at the nominal pressures of the GT or AGTA, the water cannot leak out of the pores because of the higher bubble point established by the hydrophobicity of the porous hollow fibers. While the IATCS fluid is in equilibrium with the cabin atmosphere for dissolve air, according to Henry's law, it is not saturated with air as it would be if the IATCS coolant were also at 1 atm. There is residual solubility of the IATCS at the GT because the pressure is about 166 kPa (24 psia). Because of this residual solubility, an air bubble introduced into the solution would begin to dissolve. If a portion of it made it to the trap before it completely dissolved, it would enter the venting tubes because of the higher pressure of the IATCS fluid.

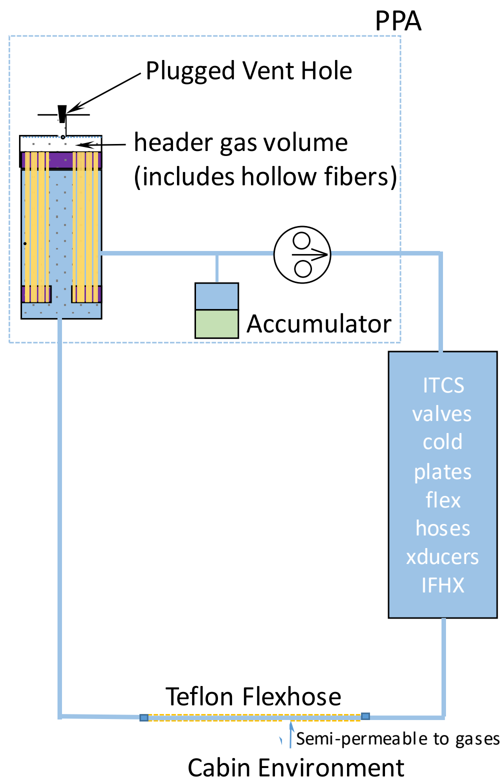

Figure 7. Flexhose Interchange with GTPA

With the plug in place, the coolant is also in equilibrium with the 1 atm of air because of the permeability of the PTFE (Teflon) Flexhoses to gas, see Figure 7. Again the solubility of the coolant in the gas trap would be based on it's local pressure of about 166 kPa (24 psia). A free gas bubble introduced in the circulating coolant would likewise begin to dissove due to the residual solubility of the coolant at higher pressure. As the bubble flows into the GT or AGTA, it would also cross the porous hydrophobic fiber walls into the vent space because of the higher pressure of the coolant at 166 kPa (24 psia) compared to the initial pressure of the vent space 101 kPa (14.7 psia). As the gas enters the vent space, because of it's fixed space (a closed volume, because of the plug), its pressure would rise. There is a limit, of course, to the size of the bubble that could be absorbed into the fixed vent space. Having absorbed the bubble, the pressure in the GT or AGTA vent space would be above 101 kPa (14.7 psia) and therefore out of the equilibrium pressure established by the flexhoses, so the additional air absorbed by the GT or AGTA, would eventually dissolve into the coolant and an equivalent amount of gas would pass out the flexhoses into the cabin. In theory, for a GT or AGTA coolant pressure of 166 kPa (24 psia), the size of bubble that can be absorbed with a plugged GT or AGTA would be 116 mL (7.1 in^3) or 301 mL (18.35 in^3). However, transiently, the bypass checkvalve could limit the amount of gas absorbed.

For large amounts of free gas that might occur when a payload is attached, the capacity of the GT or AGTA could be exceeded and the gas would flow through the bypass leg to the pump impeller. To avoid this, such operations are planned to be performed with the GTPA deinstalled.

B. 180-Day Contingency Vacuum Operations

Eliminating the water vapor losses of the AGTA, discussed in Section I.B of this paper, is the primary purpose of the GTPAs. Current coolant losses of ~0.5% per month, or ~3% total over a six-month period, are due to chronic leaks through the fittings and connectors. While the PTFE flexhoses are semi-permeable to non-polar gases such as nitrogen and oxygen, they are only negligibly permeable to water because of the hydrophobicity of PTFE.[4] The chronic leak rates are driven by the differential pressure across the leak points. Because the minimum pressure in the coolant loops is about 20 psia (a delta pressure of about 5 psid) in nominal operations, this yields 4-fold increase in pressure differential going to vacuum. This very conservative assumption would yield a chronic leak rate of ~2% per month, or 12% over a six month period, that would still be acceptable for operation. A more realistic assumption is to based the driving pressure on the mean pressure of the system. In this case there would be about at 1.4-fold increase in the pressure differential on average, amounting to a 4.3% loss over a 6 month period in a vacuum environment.

C. Pressure Effects During Filling Operations

Periodically, the IATCS coolant loops need to be filled due to losses from chronic and acute leaks. When this occurs, the nitrogen pad on the PPA accumulator is vented to ambient to facilitate the filling process. Due to the suction of the PPA, with the nitrogen pad vented, the inlet pressure to the pump is about 94.5 kPa (13.7 psia). If pressures below 101 kPa (14.7 psia) occurred at the membrane fibers of the GTs or AGTAs, then an influx of gas back through the membrane pores and into the coolant space would occur. With the plugs in place, the total amount of gas that could be infused from the vent space within the GT as this space goes from 101 kPa (14.7 psia) to 94.5 kPa (13.7 psia) is 7.4 mL (0.45 in^3). This free gas would be retrained by the hydrophilic outer tubes, see Figure 4. Once the fill operation is completed this gas would be driven back into the vent space as normal pressures are established. This operation has been performed without the plugs in place where the influx of gas would be constant during the fill. This has occurred with no observable change in delta pressure across the GT, indicating that the pressure at the membranes is probably above 101 kPa (14.7 psia). The GT have a pressure drop of about 20.7 kPa (3 psid), and most of that is likely to be across the hydrophilic outer tubes.

For pressures below 101 kPa (14.7 psia), an influx of 28.7 mL (1.75 in^3) of air would be expected to be release from the vent space of the plugged AGTA. This larger quantity relative to the GT is due to the additional volume of vent space in the 15,000 fibers. However, this gas would not be not be contained by the AGTA as there are no hydrophilic outer tubes as are present in the GT. Previous testing shows that this influx of air from the micropores appears as tiny bubbles, akin to what is seen in champagne.[8] As this influx would occur relatively slowly and be constituted of these tiny bubbles, this would not affect operations of the PPA. However during filling, some of the bubbles will flow into the accumulator, but this will be of little consequence, due to the small amount of gas that will be ingested.

Because the pressure drop across the AGTA is only 15.2 kPa (2.2 psid)[9], it is likely that the outer layers of the fiber bundle would be below 101 kPa (14.7 psia). Because of this, it is recommended that filling operations be done <u>with</u> the GTPAs installed, otherwise this may result in a significant increase in gas entering the accumulator during fill operations.

Independent of the gas traps and the GTPAs, with an air solubility of the IATCS fluid in equilibrium with 1 atm, according to Henry's law, the pressure reduction to 94.5 kPa (13.7 psia) during filling necessarily means that the solubility of the becomes transiently supersaturated. If all the excess dissolved air above the solubility limit for 94.5 kPa (13.7 psia) were to come out of solution at the pump inlet, this would amount to 0.12% by volume of free gas. As this is below the PPA specification of 0.5% by volume of free gas, there is no issue.[1]

D. Temperature Effects During Normal Operations

Henry's constant decreases as solution temperature increases. That is, as the temperature of the solution increases, for a given pressure of gas, less gas will be in solution in equilibrium conditions. Given that the coolant loops vary in temperature from as cold as 3.33 ºC (38 ºF) to as warm as 23.9 ºC (75 ºF), the question arises will the gas be coming out of solution as the coolant warms as it circulates through the loop? Since the warm point occurs upstream of the pump, with the plugs in place, this free gas could potentially fill and bypass the GT or AGTA and then violate the pump specification or result is a vapor locked impeller. To address this, the temperature dependency of Henry's constant, *H(T)*, was determined for aqueous solutions of air. This determination can be approximated over a modest temperature range using the Van't Hoff extrapolation[10]:

$$H(T) = H^{\circ} \times \exp\left[\frac{-\Delta_{\text{sol}} H}{R}\left(\frac{1}{T} - \frac{1}{T^{\circ}}\right)\right]$$

where H^o is the value of Henry's constant at the reference temperature T^o (298 K), $\Delta_{sol}H$ is the solute enthalpy of solution, and R is the molar gas constant. As the traps are plugged, the equilibrium of the coolant with the cabin air is through the PTFE flexhoses, that are close to the coldest temperature before entering payload and avionics racks, and are close to the warmest temperatures after the payloads. Since these flexhoses are distributed throughout the coolant loop, and the residence time within the flexhoses is small, the equilibrium solubility will be close to the mean temperature, T_{mean} ~13.6 ºC (56.5 ºF) or 286.8 K, and the lowest solubility in the loop will occur at T_{max} ~ 23.9 ºC (75 ºF) or 297 K. When *H(T)* is determined for these two system temperatures, the differential solubility is 28% lower at the warmer temperature. If the coolant were at 101 kPa (14.7 psia), then as it warmed to T_{max}, 14.5% of the dissolved air would become free gas. However the residual solubility of the coolant due to the system pressure is almost always greater than 14.5%. As long as the system pressure is above 117 kPa (17 psia) there would not be any free gas.

During filling operations, as system pressure drops as low as 94.5 kPa (13.7 psia) the maximum amount of free gas that could evolve by the warming and the reduced pressure would be 0.39% by volume, which is lower than the allowed pump specification of 0.5%.

E. Humidity Effects

It has been suggested that the plugging operation would create higer humidity inside the venting fibers that could promote microbial growth and thereby reduce the hydrophobicity of the membrane. This in turn could lead to leaking and loss of function of the GTs or AGTAs. However, the GTs and AGTAs are well controlled for microbial growth by maintaining effective concentrations of the microbicide Orthophalaldehyde. Also, the GT fibers are 0.254 m (10 inches) long, and the inner diameter of the fibers are only 220 μm, and given the small convection environment of the PPAs, most of the length of the fiber has nearly always been saturated with water vapor over the many years of continuous operatin and have not resulted in leaks. Therefore this is not a credible issue.

IV. Conclusions

The GTPAs have been successfully built according to the requirements, and based on engineering evaluations, should meet the goal of providing additional time needed for crew to don protective gear and move to a safe haven in the event of an ammonia leak into the IATCS. The GTPAs also retire the risk for 180-day contingency operations of the ISS in the event of a loss of cabin atmosphere, thus providing for a controlled deorbit to minimize the risk to public

Figure 8. GTPA installed on Node 3 MTL GT

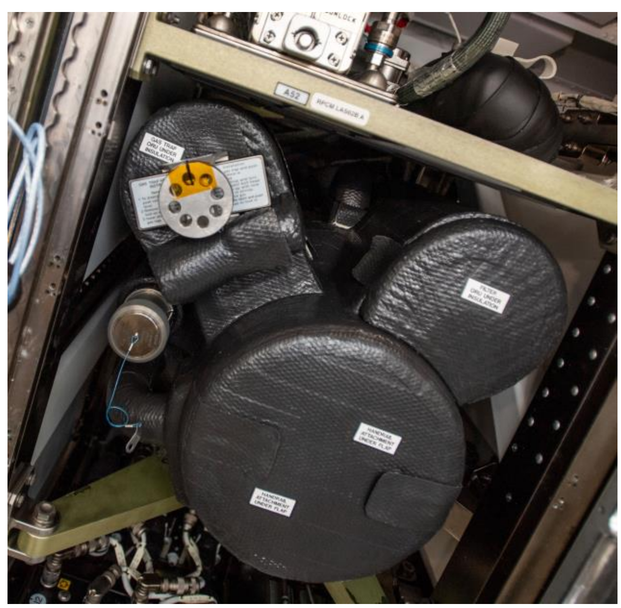

Figure 9. GTPA installed on USL MTL GT

safety. An analysis shows that the GTPAs will not affect normal operations and will even provide limited gas trapping function while plugged. During the reduced IATCS loop pressure of the filling operations, installed GTPAs will limit gas infusion, especially for the AGTA. Temperature and pressure effects on solubility will not result in violation of the pump specification for free gas with the GTPAs installed.

Acknowledgments

TBD.

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