Trending of Overboard Leakage of ISS Cabin Atmosphere

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The International Space Station (ISS) overboard leakage of cabin atmosphere is continually tracked to identify new or aggravated leaks and to provide information for planning of nitrogen supply to the ISS. The overboard leakage is difficult to trend with various atmosphere constituents being added and removed. Changes to nitrogen partial pressure is the nominal means of trending the overboard leakage. This paper summarizes the method of the overboard leakage trending and presents findings from the trending.

Nomenclature

ATV	=	Automated Transfer Vehicle
БМП	=	RSOS Micropurification Unit
CDRA	=	Carbon Dioxide Removal Assembly
COF	=	Columbus Module
EVA	=	Extra Vehicular Activities
ISS	=	International Space Station
IVA	=	Intra-Vehicular Activity
JEM	=	Japanese Experiment Module
JLP	=	Japanese Experiment Logistics Module Pressurized Section
JPM	=	JEM – Pressurized Module
MCA	=	Mass Constituent Analyzer
NORS	=	Nitrogen/Oxygen Recharge System
OGA	=	Oxygen Generation Assembly
PMM	=	Permanent Multipurpose Module
RSOS	=	Russian On-Orbit Segment
ULD	=	Ultrasonic Leak Detector
USOS	=	United States On-Orbit Segment
VES	=	Vacuum Exhaust System

I. Introduction

Leakage of the ISS cabin atmosphere overboard leads to the consumption of nitrogen and air from ISS and visiting vehicle reserves. Trending of the overboard leakage is performed to ensure the ISS reserves and resupply of nitrogen are sufficient for maintaining the ISS total pressure, supporting operational uses, and use of nitrogen to support payload experiments.

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ISS cabin is maintained at a nominal total pressure between 96.5 kPa (14.0 psia) and 102.7 kPa (14.9 psia) and is composed of oxygen, nitrogen, small amounts of CO2 and other trace gases. The nominal total pressure allows for a livable environment similar to the pressures seen on the ground. The free air volume of the cabin also plays an important role due to the buffer it provides over the range of the nominal pressures. The free air volume is defined as the volume of the ISS that the atmosphere can equalize into. Volume taken up by structure or pressure vessels is not included. The free air volume has increased over the life of ISS due to the additions of modules to the United States On-Orbit Segment (USOS) and Russian On-Orbit Segment (RSOS). The increased ISS volume has extended the response time to having to add nitrogen or air for a given leak rate as well as adding oxygen in support of metabolic needs. At the beginning of 2008 the free air volume of the ISS was 434 m^3 (15,318 ft^3). After the addition of multiple modules, the ISS free air volume was 899 m^3 (31,741 ft^3) by March 2011. Visiting vehicles other than Shuttle are included in the volumes numbers. There are nominally 4 visiting vehicles docked to the ISS with the typical complement of vehicles consisting of 2 Soyuz and 2 Progress. An evaluation of a theoretical leak rate of 1 lbm/day air illustrates the benefit of the additional volume to the ISS. At the beginning of 2008, a 0.45 kg/day (1 lbm/day) air would have taken 70 days to drop the ISS total pressure from 102.7 kPa (14.9 psia) to 96.5 kPa (14.0 psia). However by March 2011, a 0.45 kg/day (1 lbm/day) air leak rate would have taken 146 days to drop the ISS total pressure from 102.7 kPa (14.9 psia) to 96.5 kPa (14.0 psia).

The downside to increased ISS volume is that each module that is added has a small amount of nominal leakage associated with it and it also increases the potential locations that a leakage issue may occur. To ensure that overboard leakage is minimized, all modules that are added to the ISS are put through a stringent ground testing program that evaluates leakage of the module's individual feedthroughs (holes in the pressure shell) in addition to leak testing the overall module. Experience has shown that module leakage measured on the ground is lower than that observed once modules are on-orbit. Trending of data on-orbit cannot isolate individual modules, but an overall comparison of observed on-orbit leakage to ground leakage has shown that on-orbit leakage is 12-15 times higher. The higher leakage is attributed to the additional interfaces to mate modules together and increases in leakage due to launch vibration. Table 3 in the Appendix provides a list of ISS modules and their respective free air volume, specification leakage, and ground leakage. Figure 8 below shows in the Appendix illustrates the configuration of the modules on ISS that are referenced in the Table 3 Appendix.

To maintain the cabin total pressure within the 14.0 psia to 14.9 psia range oxygen and nitrogen has to be added back to the cabin. Oxygen needs are driven by the metabolic ISS crew demand. The amount of lost oxygen due to leakage is small in comparison and can be accounted for using the oxygen generation capability or visiting vehicle oxygen reserves. The ISS oxygen generation capability is performed by the Elektron in the RSOS and the Oxygen Generation Assembly (OGA) in the USOS. The Elektron and OGA generate oxygen through electrolysis of water. Nitrogen however is not metabolized and must be added back to the cabin after losses due to leakage or operations. The nitrogen is usually added to cabin from the Shuttle or Progress tanks, but the ISS also has 2 tanks of nitrogen that are attached to the US Joint Airlock. The nitrogen in the Joint Airlock tanks is used only after other resources have been expended to protect a reserve level of nitrogen on the station. If the nitrogen from the tanks is used, then the tanks are replenished from the Shuttle tanks. Post Shuttle retirement the ISS will not only lose the current ability to replenish the Airlock tanks, but lose the additions of nitrogen Shuttle usually provides to the cabin. A new resupply capability called Nitrogen/Oxygen Recharge System (NORS) is being developed to replace the Shuttle nitrogen capability.[2] NORS will consist of smaller intra-vehicular activity (IVA) tanks that can hold up to 7000 psia of oxygen or nitrogen and the necessary support equipment. The first NORS tanks are not expected to be flown until 2013 timeframe. Until the NORS tanks are available, the nitrogen from the Airlock tanks will be utilized to maintain the ISS total pressure as well as, Automated Transfer Vehicle (ATV) and Progress tanks.

Operational losses account for lost nitrogen overboard in addition to leakage. Operational losses consist of air vented for vehicle undocking, Extra Vehicular Activities (EVA) airlock depressurization, losses during CO_2 venting, RSOS Micropurification Unit (БМП) regeneration, and venting of air from Payload experiments. The lost air from undocking is a result of depressurization of the vestibule volume between the ISS and the visiting vehicle. For both RSOS and USOS EVAs an airlock must be depressurized to be able to open the hatch. The USOS EVAs vent less gas due to the use of the Depress Pump that pumps air out of the US Airlock to the cabin. However, the Depress Pump can only be operated down to 13.8 kPa (2 psia) so the rest of the air is vented overboard. The USOS Carbon Dioxide Removal Assembly (CDRA) and RSOS Vozdukh remove CO2 from the cabin and vent it overboard. The CO2 venting is efficient, but there are some inherent losses of air that are seen during the process. The final operational loss is from Payloads. Some Payload experiments will pressurize their experiments with cabin air and will vent it through the Vacuum Exhaust System (VES) to space after completing experiments. A summary of the operational losses is provided in Table 1.

Table 1 ISS Operational Losses[3,5]

Operation	Loss
Shuttle Undocking	16.5 lbm air per mission
Progress/Soyuz/ATV	0.64 lbm air per mission
HTV/MPLM	3.5 lbm air per mission
CDRA	0.048 lbm O_2/day, 0.084 lbm N_2/day
Vozdukh	Up to 0.13 lbm/day air
БМП	0.002 lbm/day air
Payloads	Up to 78 lbm/year N2 (can be cabin atmosphere and/or Airlock nitrogen)
RS EVAs	35.3 lbm air per EVA
US EVAs	3.6 lbm air per EVA

II. Trending Methodology

The trending of cabin leakage is approached by tracking the amount of nitrogen in the cabin atmosphere. Nitrogen is chosen since it is not consumed by the crew or animals. Total mass or oxygen mass in the cabin could be used, but the metabolic rate of the crew would have to be tracked. Variability in metabolic rates from crew member to crew member would add additional error to the trending. Nitrogen mass decays slowly allowing monitoring of the nitrogen mass over long periods of time. The Ideal Gas Law, Eq. (1), is used to calculate the nitrogen mass from the nitrogen partial pressure measured by the Major Constituent Analyzer (MCA) along with the free air volume and temperature to generate nitrogen mass. The temperature on ISS is controlled by multiple heat exchangers in multiple modules so the temperature can vary from location to location. To account for this, the temperature used in Eq. (1) is determined by taking a volume weighted average of temperatures across the ISS. Eq. (2) provides a formula that is used to calculate the volume weighted temperature. The temperature in Node 1 was taken to be the average temperature of the A/L and Lab (Eq. 3). The assumption is made because there is no temperature sensor in Node 1.

$$m_{nitrogen} = \frac{P_{nitrogen} V_{ISS}}{R_{Nitrogen} T_{ISS}} \tag{1}$$

$$\begin{aligned} T_{ISS} = {} & T_{Lab}\left(\frac{V_{Lab}}{V_{Total}}\right) + T_{Airlock}\left(\frac{V_{Airlock}}{V_{Total}}\right) + T_{Node1}\left(\frac{V_{Node1}}{V_{Total}}\right) + T_{Node2}\left(\frac{V_{Node2}}{V_{Total}}\right) + T_{Node3}\left(\frac{V_{Node3}}{V_{Total}}\right) + \\ & T_{SM}\left(\frac{V_{SM}}{V_{Total}}\right) + T_{FGB}\left(\frac{V_{FGB}}{V_{Total}}\right) + T_{COF}\left(\frac{V_{COF}}{V_{Total}}\right) + T_{JPM}\left(\frac{V_{JPM}}{V_{Total}}\right) + T_{JLP}\left(\frac{V_{JLP}}{V_{Total}}\right) + \\ & T_{MRM1}\left(\frac{V_{MRM1}}{V_{Total}}\right) + T_{MRM2}\left(\frac{V_{MRM2}}{V_{Total}}\right) \end{aligned} \tag{2}$$

$$T_{Node1} = \frac{T_{Lab} + T_{Airlock}}{2} \tag{3}$$

The nitrogen mass is plotted versus time and quiescent periods with minimal activity are chosen to apply a least squares fit on the data. Any time periods around dockings, undockings, EVAs, or gas introductions are not included in the selection. The least squares fit using the Robust Bi-Square option provided in MATLAB®™ software program is used to ignore outliers in the data. An example of the selection pressure and resulting fit is shown in Figure 1. Once the rate of nitrogen mass loss is identified, the nitrogen rate needs to be converted to an air rate and oxygen rate. To accomplish this it is assumed that the ISS atmosphere is made up of oxygen and nitrogen only ignoring the other trace gases. The assumption of composition make-up of the atmosphere can be applied to the Ideal Gas Law to achieve the following equations (Eqs. 4 & 5) to convert mass rates from one gas to another. The results of the fits provide the total cabin air loss. A component of the losses are from the operational losses discussed earlier, but for the purposes of trending cabin air loss is assumed to be equivalent to cabin air leakage.

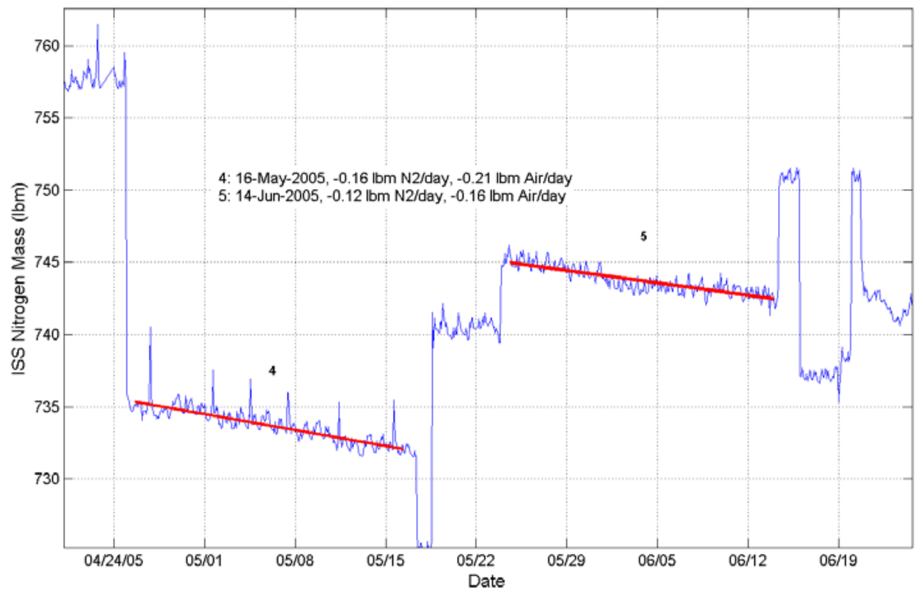

Figure 1 Example of Nitrogen Mass Selection for Trendline

$$m_{O_2} = \frac{\chi_{O_2} R_{N_2}}{\chi_{N_2} R_{O_2}} m_{N_2} \tag{4}$$

$$m_{Air} = \frac{\chi_{Air} R_{N_2}}{\chi_{N_2} R_{Air}} m_{N_2} \tag{5}$$

Where m is mass,
X is gas concentration, and
R is gas constant.

III. Current Trending Results

The current trending results cover data from October 2004 through February 2011. During this time period the ISS leakage rate has increased from ~0.064 kg/day (0.14 lbm/day air) to ~0.227 kg/day (0.50 lbm/day air). Table 2 provides a summary of the leakage by quarter. During this time period the ISS has grown considerably, but closer inspection of 2007 – 2008 timeframe shows that there was an increase of leakage prior to the addition of Node 2 in November 2007 (Figure 3). Node 2 was the first of the module additions in recent years. The Columbus Orbiting Facility module (COF), Japanese Experiment Module (JEM) – Pressurized Module (JPM), and Japanese Experiment Logistics Module Pressurized Section (JLP) were added in the first half of 2008. The cause of the initial increase was not identified. Due to the limitations of the trending method it is difficult to pinpoint specific timing of any shifts in rates less than one order of magnitude. Events around the time of the initial increase include the undocking of 24P Progress (1 August 2007), docking of 26P Progress (5 August 2007) and STS-118/13A.1 Flight (10 August 2007). However, this limited list is not inclusive of all potential events affecting leakage rates. Any changes to systems with overboard vents, hatches, windows, or feedthroughs could have an impact.

After the increase in the second half of 2007 and the additions of modules in the first half of 2008 the ISS leakage settled in around 0.181 kg/day air (0.4 lbm/day). However, by the end of 2010 the leakage increased to around 0.227 kg/day air (0.5 lbm/day). MRM-2 (13 November 2009), Node 3 (12 February 2010), and MRM-1 (20 May 2010) were the module additions during this timeframe. As seen in Figure 4 and Figure 5, the data does have significant spread, but is sufficient for identifying significant leakage issues and establishing a leakage number for gas logistics planning purposes. The leakage planning number being used in 2011 is 0.227 kg/day air (0.5 lbm/day), but the addition of Permanent Multipurpose Module (PMM) is being evaluated for future adjustments to the planning number. The PMM ground leakage result of 0.095 kg/day air (0.21 lbm/day) in Table 3 is the result of an analysis of leak tests of individual paths of external leakage. There is some hope that the actual whole module performance exceeds the analysis result. If the PMM addition to the ISS results in an overall 0.095 kg/day air (0.21 lbm/day) net increase of leakage then it will drive re-evaluation of ATV gas loading and put additional emphasis on delivery of NORS tanks post Shuttle retirement.

Table 2 ISS Leakage by Quarter

Quarter	Median Air Leakage Rate (lbm/day)	Average Air Leakage Rate (lbm/day)
2004Q4	-0.14	-0.14
2005Q1	-0.15	-0.15
2005Q2	-0.16	-0.15
2005Q3	-0.13	-0.13
2005Q4	-0.13	-0.13
2006Q1	-0.22	-0.22
2006Q2	-0.22	-0.27
2006Q3	-0.15	-0.16
2006Q4	-0.20	-0.17
2007Q1	-	-
2007Q2	-0.24	-0.24
2007Q3	-0.34	-0.39
2007Q4	-0.33	-0.40
2008Q1	-0.39	-0.37
2008Q2	-0.44	-0.45
2008Q3	-0.40	-0.40
2008Q4	-0.44	-0.44
2009Q1	-0.38	-0.38
2009Q2	-0.40	-0.41
2009Q3	-0.54	-0.50
2009Q4	-0.53	-0.53
2010Q1	-0.47	-0.46
2010Q2	-0.42	-0.42
2010Q3	-0.50	-0.52
2010Q4	-0.53	-0.51
2011Q1	-0.70	-0.74

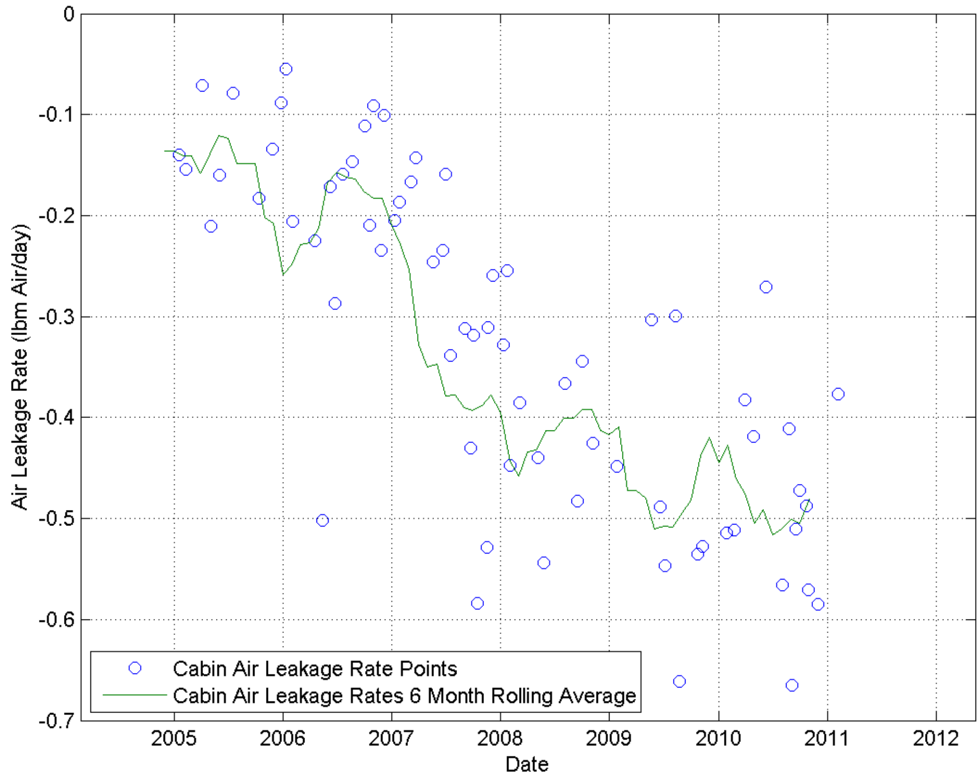

Figure 2 Leakage Data and Running Average

Figure 3 Leakage Data 2007 and 2008

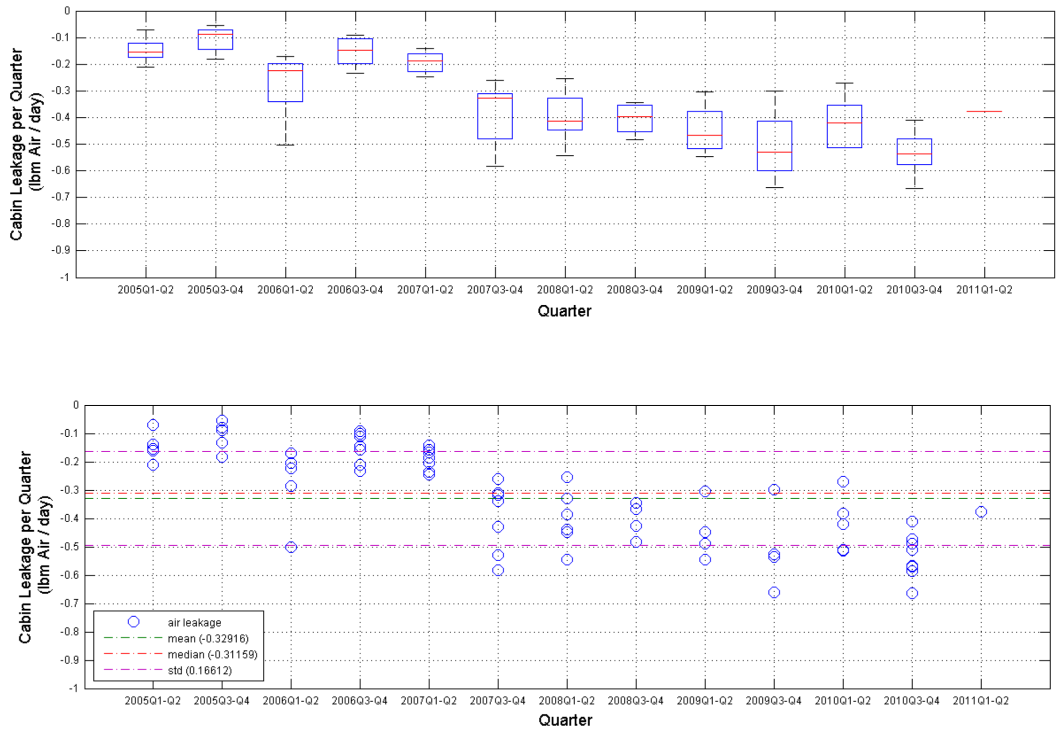

Figure 4 ISS Leakage Boxplots

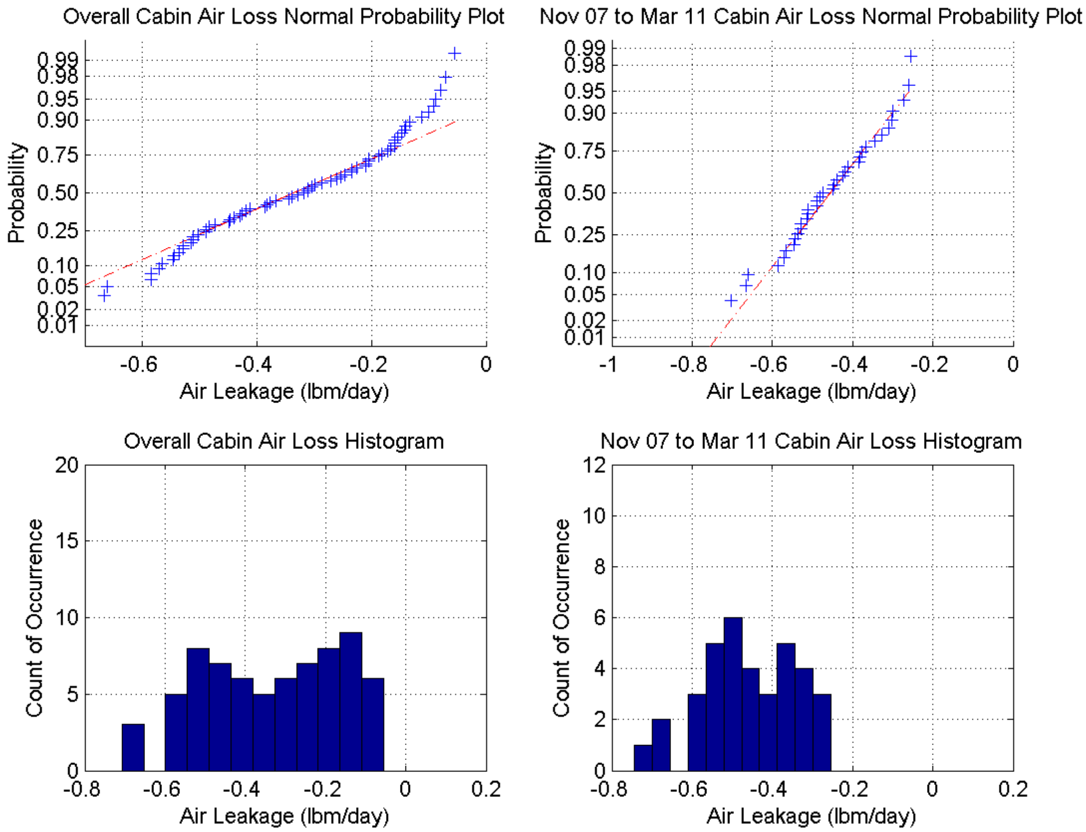

Figure 5 Leakage Probability Plot

IV. ISS Leakage Events

The ISS has had only one on-orbit leakage event since being on-orbit. A significant pressure drop was detected in late December 2003 and continued through mid-January 2004. On 5 January 2004, a 2.1 kPa (0.3 psi) decrease in total pressure over 5 days was noticed by Flight Controllers in MCC-Houston. The rate did not endanger the crew, but required scheduling represses and the use of nitrogen reserves. The decrease in total pressure and represses are shown in Figure 6. To identify the source of the leakage a plan to use the Ultrasonic Leak Detector (ULD) for surveys of suspect locations, a checkout of the Vozdukh and BMP, and isolation of the RSOS and USOS segments was developed. The initial use of the ULD on 6 January 2004 focused on hatches, PMA 1, and the Lab window, but it didn't result in finding the leak. However after the Vozdukh and BMP checkout provided zero results, the crew performed additional ULD checks on 11 January 2004 and found significant noise from the Lab window U-Jumper. The U-Jumper is a metal bellows flex hose that provides a vacuum to a inner volume of the window. The vacuum prevents moisture from accumulating on the tension side (outboard) of the primary pressure pane and ensures positive pressure outboard. The flex hose was removed by the crew once it was identified thus stopping the leak as can be seen in Figure 6.[4]

Evaluation of the nitrogen partial pressure in Figure 7 showed that the leaky hose caused a leak rate of approximately 0.907 kg/day air (2.0 lbm/day). The 21-day leak resulted in approximately 19.1 kg (42.0 lbm) air being lost.[4]

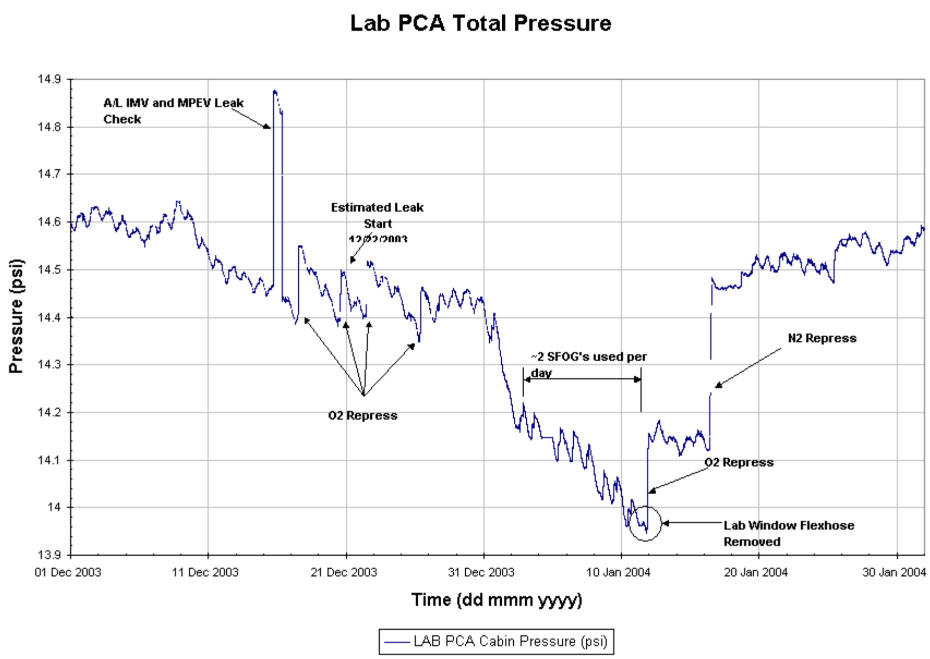

Figure 6 December 2003 Leakage Event Total Pressure[4]

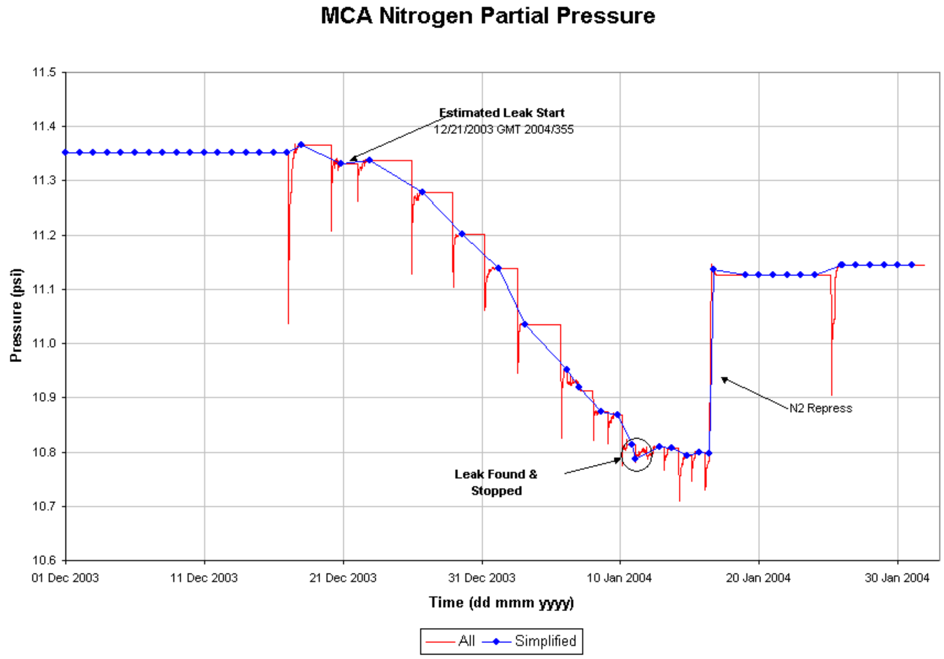

Figure 7 December 2003 Leakage Event Nitrogen Partial Pressure[4]

V. Conclusion

Leakage of air on ISS can be tracked by monitoring the nitrogen partial pressure and calculating the nitrogen mass in the ISS atmosphere. The trending of leakage has shown that the leak rate has increased from ~0.064 kg/day air (0.14 lbm/day) in 2004 to ~0.227 kg/day air (0.5 lbm/day) in 2011. At these relative low levels the sources of the leakage cannot be identified, but a portion of the increase is assumed to be from the 7 additional modules that have been added to ISS.

The trending of leakage is an important part of sustaining ISS. The leakage data goes into the planning of nitrogen resupply to the ISS, but also identifies significant leakage issues. The retirement of the Shuttle has put ISS resupply into increased focus. Gas logistics must be evaluated with any increases in leakage. Previous operation of ISS has counted on the abundant amount of nitrogen that Shuttle could bring up. Post Shuttle retirement the resupply of nitrogen will be performed by NORS tanks, ATV vehicles, and Progress vehicles.

Appendix

Table 3 ISS Module Volumes and Leakage Data[1,7]

Segment	Module	Free-Air Volume (ft^3)	Specification Leakage (lbm/day)	Actual Ground Leakage (lbm/day)
USOS	Lab	3450.60	0.109	0.006
USOS	Lab / N1 Vestibule	46.80	0.005	0.00027
USOS	Node 1	1947.86	0.117	0.005
USOS	Airlock	1108.25	0.1	0.000114
USOS	PMA 1	202.95	0.2	0.00089
USOS	Z1 Dome	52.89	0.0001	-
RS	FGB	2154.20	0.0044	0.00064
RS	FGB/SM Vestibule	32.00	0.00044	0.0008
RS	SM	3073.00	0.0044	0.00002
RS	DC1	441.00	0.0005	0.0000196
RS	DC1 Vestibule*	32.00	0.00044	0.0008
RS	MRM 2****	441.00	0.0005	0.0000196

Segment	Module	Free-Air Volume (ft^3)	Specification Leakage (lbm/day)	Actual Ground Leakage (lbm/day)
RS	MRM 2 Vestibule*	32.00	0.00044	0.0008
RS	MRM 1****	441.00	-	-
RS	MRM 1 Vestibule	32.00	-	-
RS	Soyuz	363.00	0.002593	0.000125
RS	Soyuz Vestibule	8.83	-	0.0008
RS	Soyuz	363.00	0.002593	0.000125
RS	Soyuz Vestibule	8.83	-	0.0008
RS	Soyuz***	363.00	0.002593	0.000125
RS	Soyuz Vestibule	8.83	-	0.0008
RS	Progress (x1)	212.00	0.00264	0.00000616
RS	Progress Vestibule (x1)*	8.83	-	0.0008
USOS	Node 2*	2190.00	0.117	0.005
USOS	N2 / Lab Vestibule	46.80	0.005	0.00027
USOS	Node 3***	2190.00	0.117	0.005
USOS	N3 / N1 Vestibule	46.80	0.005	0.00027
USOS	Cupola	59.40	-	-
USOS	Cupola / N3 Vestibule	46.80	0.005	0.00027
APM	COF*	2261.00	0.5	0.0017
APM	COF Vestibule*	46.80	0.0001	0.00027
JEM	ELM	1389.56	0.2	0.00037
JEM	ELM Vestibule*	46.80	0.0001	0.00027
JEM	PM	4473.00	0.3	0.000326
JEM	PM Vestibule	46.80	0.0001	-
USOS	PMM (MPLM)††	1590	0.24	0.21
USOS	PMM Vestibule	46.80	0.005	0.00027

*ELT data is estimated based on similar modules since it was not able to be obtained for this analysis
**CEV leak rate is scaled back from specification to compensate for not being present until 2014
***Estimated on-orbit leakage is by similarity for these modules, not volume weighted as rest are
****Module free-air volume is estimated
*****COTS rate from SSP 50808 rev A para. 3.3.4.4
†Overall total values include future visiting vehicles as described
††Nominally leakage is significantly higher on-orbit than on the ground. This is an unconservative estimate for PMM on-orbit leakage due to unconventionally high ground leakage requirement/testing

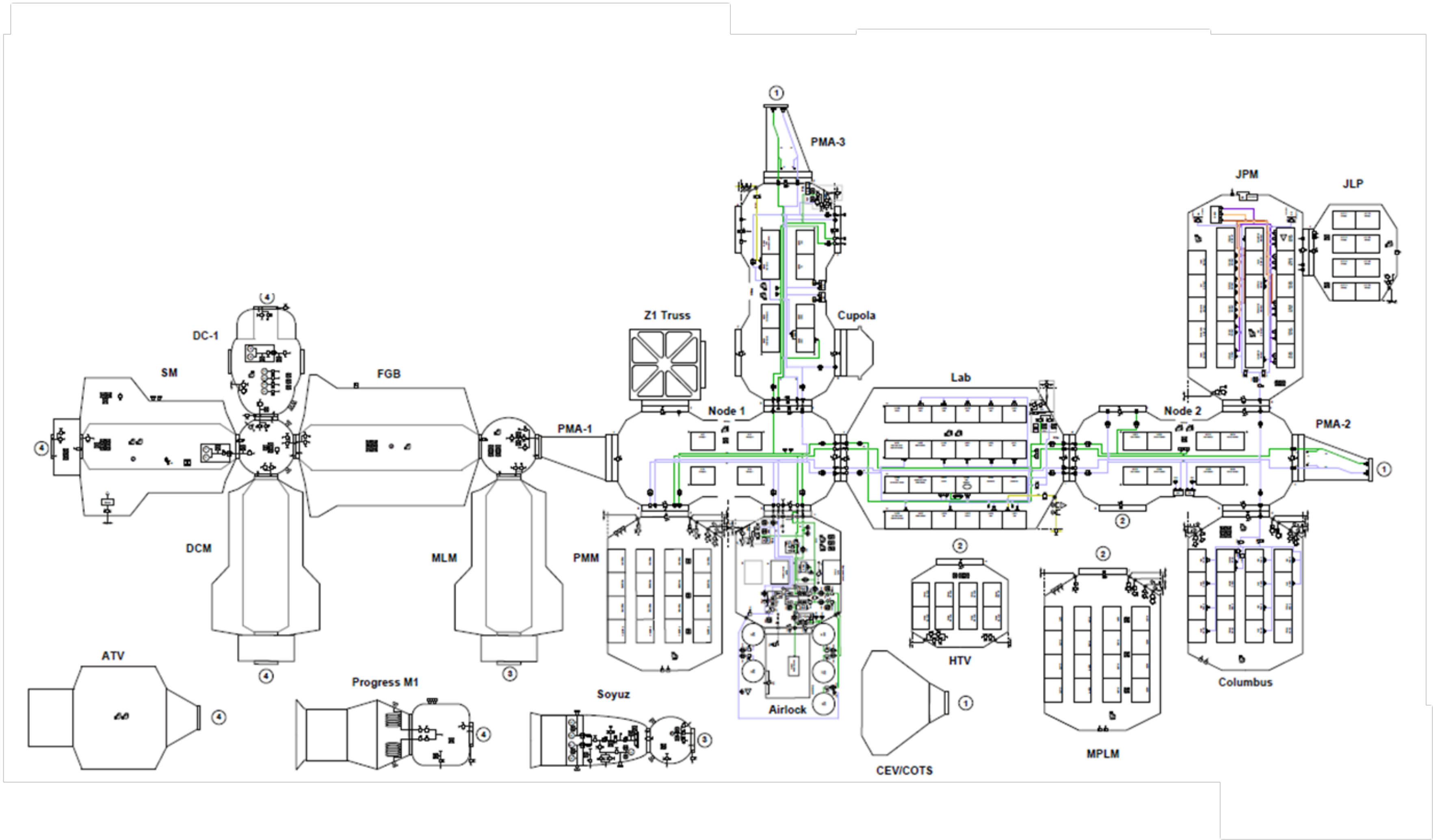

Figure 8 ISS Schematic at Assembly Complete[5]

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