12-16 July 2015, Bellevue, Washington

Report on ISS O2 Production, Gas Supply & Partial Pressure Management

Ryan N. Schaezler[1] and Anthony J. Cook[2]
The Boeing Company, Houston, TX, 77059

Oxygen is used on International Space Station (ISS) for metabolic support and denitrogenation procedures prior to Extra-Vehicular Activities. Nitrogen is used to maintain total pressure and account for losses associated with leakage and operational losses. Oxygen and nitrogen have been supplied by various visiting vehicles such as the Progress and Shuttle in addition to the on-orbit oxygen production capability. Starting in 2014, new high pressure oxygen/nitrogen tanks are available to launch on commercial cargo vehicles and will replace the high pressure gas source that Shuttle used to provide. To maintain a habitable atmosphere the oxygen and nitrogen partial pressures are controlled between upper and lower bounds. The full range of the allowable partial pressures along with the increased ISS cabin volume are utilized as a buffer allowing days to pass between oxygen production or direct addition of oxygen and nitrogen to the atmosphere from reserves. This paper summarizes the amount of gas supplied and produced from all of the sources and describes past experience of managing partial pressures along with the range of management options available to the ISS.

I. Introduction

Ensuring that the ISS Cabin has a habitable atmosphere is one of the primary goals of the Environmental Control and Life Support (ECLS) system. Significant to satisfying this goal is the control and resupply of oxygen (O2) and nitrogen (N2). The oxygen partial pressure is maintained at a range of 146 – 178 mmHg (2.82 – 3.44 psi) and the total pressure is maintained between 724 – 770.5 mmHg (14.0 – 14.9 psia). Oxygen partial pressures are maintained primarily by electrolysis of water and is supplemented with represses from stored resources as necessary. Total pressure is maintained solely from represses of air or nitrogen from stored resources. The ranges in pressures allow some flexibility to change oxygen generation rates and handle impulse events such as represses from visiting vehicles (VVs). At the ISS free air volume of 807.3 – 898.8 m3 (28508 – 31741 ft3), the full range of oxygen partial pressures represents a change of 30.8 – 34.5 kg O2 (68 – 76 lbm) while the full range of total pressure represents a change of 59 – 66 kg (130 – 146 lbm) air.

The current volume of the ISS is significantly larger compared to the earlier years of operation. At the beginning of 2008 the free air volume of the ISS was 434 m3 (15,318 ft3). After the addition of multiple modules, the ISS free air volume was 899 m3 (31,741 ft3) 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.

The oxygen and nitrogen systems also satisfy many additional functions. The United States Orbital Segment (USOS) oxygen system supports contingency crew oxygen masks, EVA denitrogenation prebreathe masks, Extravehicular Mobility Units (EMUs) and other ECLS systems like the Water Processor Assembly (WPA). The USOS nitrogen system supports payloads and purge capabilities of the Oxygen Generator Assembly (OGA) and Total Organic Carbon Analyzer (TOCA).

II. ISS Monitoring Capability

The monitoring of oxygen and nitrogen partial pressure is performed by the ISS Mass Constituent Analyzer (MCA). There is one MCA in the US Lab and one MCA in Node 3. Either of the MCAs can measure the constituent

[1] Water Subsystem Lead, Environmental Control and Life Support, 3700 Bay Area Blvd, Houston, TX 77059 / HB2-40.
[2] Atmosphere Control and Supply Subsystem Lead, Environmental Control and Life Support, 3700 Bay Area Blvd, Houston, TX 77059 / HB2-40.

make-up of the atmosphere in any of the USOS modules and the Columbus and Japanese Experiment Module (JEM) modules. The MCAs utilize a set of air distribution lines and valves called the Sample Distribution System (SDS) that transmit air from each location to the active MCA. If both MCAs fail, there are a number of backup oxygen sensors that can be used. Table 1 lists the ISS oxygen sensors and provides the accuracy of each sensor. The MCA nitrogen partial pressure measurement is helpful for trending overboard leakage and assists planning of total pressure management.[5] Pressure Control Assemblies (PCAs) in several of the USOS modules provide high accuracy total pressure measurement (+/- 0.5 mmHg / +/- 0.01 psi). The total pressure measurement with the nitrogen partial pressure readings are used to determine the amount of nitrogen or air that need to be added to the cabin atmosphere.

Table 1 ISS O2 Sensor Accuracies

Sensor/Device	**ppO2 Error Band mmHg (psi)**
MCA	+/- 6 (0.12)
MCA – Dynamic Improved Accuracy	+/- ~0.7 (0.013)
CSA-O2 – Handheld Sensor	+/- 6 (0.12)
IPOM - Portable O2 Monitor	+/- 6 (0.12)
Service Module Gas Analyzer	+/- 12 (0.23)
Columbus PPOS	+/- 5.5 (0.11)

III. ISS Oxygen Systems and Resupply

Adding oxygen to the atmosphere can be accomplished through the following means:

- Oxygen generation
- Oxygen repress from stored high pressure oxygen
- Oxygen repress from visiting vehicle tanks
- Oxygen repress from Solid Fuel Oxygen Generation
- Oxygen repress from high pressure resupply tanks

Electrolysis is the primary means for replacing metabolic consumption of oxygen. The Russian Elektron and USOS Oxygen Generator Assembly are the two ISS electrolysis units that perform this task. Both units have the capability to produce enough oxygen to support the entire six crew onboard the ISS. However, the Elektron is nominally restricted to a production mode that provides up to three crew of oxygen in order to prevent early failure of the hardware. A breakdown of the oxygen generation capability and the metabolic demand is provided below.

Table 2 Oxygen Generation Summary

Hardware/Crew	**Production Mode**	**Oxygen kg/day (lbm/day)**	**# of crew**
OGA	Standby	0.20 (0.44)	0.24
	25%	2.31 (5.1)	2.8
	50%	4.63 (10.2)	5.5
	100%	9.25 (20.4)	11.1
	100% day/night	5.44 (12.0)	6.5
Elektron	16Amps	1.30 (2.86)	1.6
	32 Amps*	2.59 (5.72)	3.1
	64 Amps	5.22 (11.5)	6.25
* Nominal operation limit of Elektron			

Represses from the high pressure oxygen reserves utilize the ISS oxygen system to introduce the oxygen. The oxygen system is a network of plumbing lines, regulators, pressure sensors, and valves. The main components beside the distribution lines are the Pressure Control Assembly (PCA) and Regulator Relief Assemblies (RRAs). Figure 1 gives an overview of the oxygen system. Oxygen is stored in three High Pressure Gas Tanks (HPGTs) that are installed externally on the Airlock. Two tanks are tied in together and provide the source for the High Pressure system and the single tank provides the source oxygen for the Low Pressure System. The terms High Pressure and Low Pressure indicate the intended purpose of the gas and not the pressure in the tanks. The HPGTs are all identical. The High Pressure supply oxygen is routed to the Medium Pressure RRA which reduces the pressure from a maximum of 18,892 kPa (2740 psia) to a pressure of 5861 – 6309 kPa (850 – 915 psig). The oxygen line is teed off and supplies the Airlock Umbilical Interface Assembly (UIA) to support EMUs and also goes to the Prebreathe RRA that drops the pressure to 896 – 965 kPa (130 – 140 psig) to support EVA prebreathe denitrogenation protocols using the Quick Donn Mask Assemblies (QDMAs). The Low Pressure supply oxygen is routed to the Low Pressure RRA which reduces the pressure from a maximum pressures of 18,892 kPa (2740 psia) to a pressure of 655 – 724 kPa (95 – 105 psig). From the Low Pressure RRA the oxygen is routed throughout the USOS modules as a resource and to PCAs located in the Airlock, US Lab, and Node 3. The PCAs measure the distribution pressure and contain an Oxygen Isolation Valve (OIV) that introduces oxygen to the cabin when commanded. The PCA contains a cabin total pressure sensor which is used to repress to a target total pressure using oxygen or nitrogen based on its internal software. This commanded PCA will open the OIV and close it automatically once the total pressure sensor reaches the target pressure. Direct commanding of the OIV can be performed, but the repress command provides additional levels of safety control to prevent excessive oxygen introductions. If the PCA hardware or electronics fail, then the crew can use a manual override switch to open or close the OIV.

The oxygen HPGTs have a volume of 0.43 m3 (15.2 ft3) each and can be pressurized up to 18,892 kPa (2740 psia). This provides approximately 100 kg (220 lbm) each when taking into account thermal variations and pressure sensor accuracy.

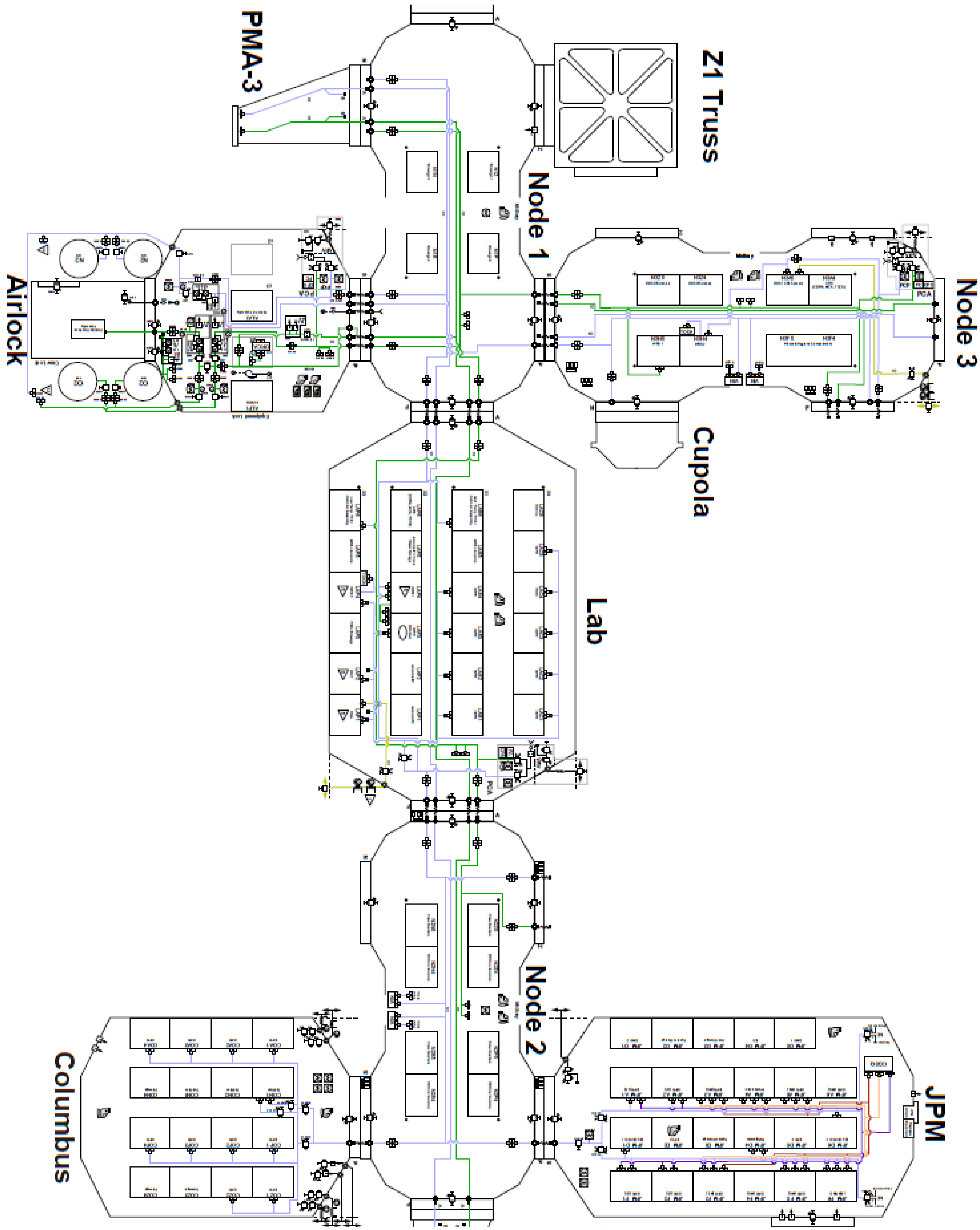

Figure 1 ISS Oxygen Systems[3]

Automated Transfer Vehicle (ATV) and Progress vehicles have tanks that can be flown with pressurized oxygen, nitrogen and/or air. The ATV can bring up a total of 100 kg (220 lbm) of oxygen while the Progress can bring up to 51 kg (112 lbm) of oxygen. Each vehicle docks on the Russian Segment (RS) and oxygen introductions require the crew to manually open a valve and close it in order to perform a repress. ATV and Progress vehicles can only be loaded with 2 varieties of gas, but the Progress has a tank of nitrogen 13 kg (29 lbm) used to pressurize the propellant system that can be dumped to the cabin after propellant is transferred to the ISS.

High pressure resupply tanks called Recharge Tank Assemblies (RTAs) are now available to launch on visiting vehicles. These tanks are provided by the Nitrogen Oxygen Resupply System (NORS). The NORS consists of the RTAs, along with the Airlock Installation Kit (AIK) and Internal Fill Kit (IFK) support hardware to integrate the tanks into the existing nitrogen and oxygen plumbing in the Airlock. NORS can either support the oxygen and nitrogen systems directly or provide an equalization transfer to the external O2 HPGTs. The NORS RTAs are 48,263 kPa (7000 psia) oxygen and nitrogen tanks with a volume of 0.076 m3 (2.68 ft3). The oxygen RTAs are filled with 38.1 kg (84 lbm) O2 and the nitrogen RTAs are filled with 28.6 kg (63 lbm) N2. The tank mass to volume ratio is optimized through the use of a Carbon Composite Overwrap Pressure Vessel (COPV) to provide robust strength and damage tolerance while minimizing the mass with respect to an equivalent metal tank. The RTAs also contain a valve assembly with a high pressure Quick Disconnect (QD), isolation valve, vent valve to enable venting of the QD to cabin before mate/demate, and a rough pressure gauge. The IFKs consist of a flex hose and an integrated regulator assembly with a flow restrictor, flow limiter, flow selector valve, check valve, dual relief valves and pneumatic/manual isolation valves. The regulator drops the NORS tank pressure from the initial launch pressure to 17,926 kPa (2600 psia). The flow limiter and flow restrictor provide fault tolerance to exceeding downstream flow rate limits to avoid any violation of hardware thermal limits. The dual relief valves provide overpressurization protection for downstream NORS components, by venting gas to cabin in the event of a regulator failure. The pneumatic/manual isolation valve has a feedback pressure loop from the relief valve outlets such that if there is any non-trivial amount of flow through the relief valves to cabin, the valve will be forced to close in order to shut off the source supply of gas to the regulator in the event of a regulator failure to avoid dumping large amounts of gas to cabin. The flow selector valve is utilized to slow flow while transferring gas directly to the HPGTs to avoid thermal overheat, or to allow a higher flow for direct supply to downstream system users. The check valve is utilized to ensure there is no backflow from the HPGTs into the NORS tanks. The flex hose then connects the integrated regulator assembly to the AIK. The AIK consists of a manifold assembly with valves to direct flow; a heater block to thermally condition the gas before it travels into the Airlock systems; and all of the structural hardware to mount the manifold to the Airlock zenith platform and cradle the installed tank.[1]

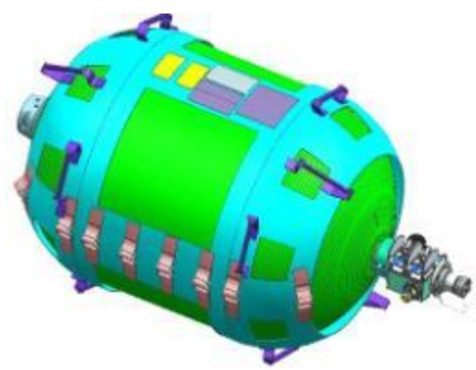

Figure 2 NORS RTA

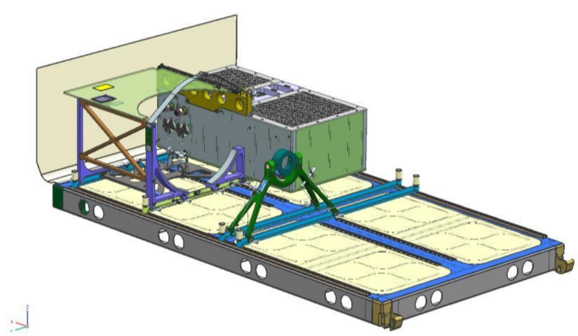

Figure 3 NORS AIK

IV. ISS Nitrogen Systems and Resupply

Adding nitrogen to the atmosphere can be accomplished through the following means:

- Nitrogen repress from stored high pressure oxygen
- Nitrogen/Air repress from visiting vehicle tanks
- Nitrogen repress from high pressure resupply tanks

The ISS Nitrogen system parallels the ISS Oxygen system in the Airlock. Represses from the high pressure nitrogen reserves utilize the internal nitrogen Airlock system to introduce nitrogen. Similar to the oxygen system, the nitrogen system is a network of plumbing lines, regulator, pressure sensors, and valves. The main difference is that the nitrogen system only has two external N2 HPGTs that are plumbed together and has only one regulator relief valve assembly instead of three. The Low Pressure RRA steps the pressure down from a maximum pressure of 18,892 kPa (2740 psia) to a pressure of 655 – 724 kPa (95 – 105 psig). Nitrogen is routed throughout the USOS modules as a resource and to PCAs located in the Airlock, US Lab, and Node 3 which allow nitrogen introduction in addition to oxygen into the cabin.

The two nitrogen HPGTs have a volume of 0.43 m3 (15.2 ft3) each and can be pressurized up to 18,892 kPa (2740 psia). This provides approximately 84 kg (185 lbm) each when taking into account thermal variations and pressure sensor accuracy.

V. Planning of Oxygen and Nitrogen Resupply

Planning of oxygen and nitrogen resupply is performed through coordination with Flight Operations, the ISS Program office, Engineering, and the International Partners (IPs). The visiting vehicle resupply gas loading has been the primary focus in the post Shuttle environment. Visiting vehicles launch schedule is determined based on other ISS needs such as resupply of food or hardware supplies. The overall need of oxygen and/or nitrogen is evaluated based on the schedule of VVs, O2 and N2 systems resource usage, planned Payloads usage, EVAs, and ISS leakage. The projected usage for both oxygen and nitrogen are modeled in addition to providing adequate nitrogen partial pressure control. Nitrogen partial pressure (ppN2) is maintained to a control point assumption between 580-595 mmHg with nitrogen being added to the cabin as required to maintain this pressure. The cabin volume is used effectively as an additional tank and resource. Using the cabin volume, ppN2 is allowed to vary between 560 mmHg and 600 mmHg based on the lack of VV gas or excess gas available prior to VV undocks. Figure 5 illustrates the approach for projecting overall N2 gas availability and the ppN2 of the cabin. The figure shows the docking of VVs on the top of the graph as designated with the vehicle name (and a "-D") and shows the undocking on the bottom of the graph with the vehicle name (and a "U"). The base assumptions of usage are as follows:

- Metabolic Usage[2]: 0.85 kg (1.874 lbm)/crew/day O2
- Cabin Leakage Rate: 0.27 kg (0.60 lbm)/day Air
- EMU Maintenance: 0.82 kg (1.8 lbm)/event, 1 event/45 days
- WPA Usage: 5.90 kg (13 lbm)/year O2
- EVA Usage: 6.8 kg (15 lbm)/EVA O2
- Payload Usage2: 17.7 kg (39 lbm)/year N2
- TOCA Usage: 6.24 kg (13.75 lbm)/year N2
- RS EVA Air Loss: 15.9 kg (35 lbm)/EVA
- US EVA Air Loss: 0.91 kg (2 lbm)/EVA

Figure 4 shows the oxygen logistics chart. The high pressure oxygen is tracked separately from the visiting vehicle gas. The separation of gas based on pressure is key to ensure that there is enough oxygen to support EVAs, which require high pressure oxygen. NORS tanks are placed on vehicles, as required, but only the minimum number of NORS tanks are added to the manifests since each NORS tank consumes a large portion of visiting vehicle weight and volume allocations. When the NORS tank does fly, the return date of the NORS tank is predetermined. It is assumed that N2 NORS tanks will stay connected in the AIK and provide nitrogen directly to the systems users. This allows the N2 NORS tank ullage left after equalization transfer to the HPGTs to be utilized for day to day nitrogen demands from the nitrogen bus. The O2 NORS tanks are assumed to be removed after an O2 HPGTs equalization transfer occurs, and will be either drained to the cabin or used for EVA support if there is enough remaining ullage in the tank. Visiting vehicle oxygen is maximized outside of what is required to maintain the nitrogen partial pressure. There are situations where there is concern that the Russian or US oxygen generators may have operational issues. If there is a concern with oxygen generator operation, additional oxygen can be loaded onto the visiting vehicle, but the resupplied oxygen is primarily provided to reduce the water required to produce oxygen by electrolysis.

There are requirements to maintain reserve levels of both oxygen and nitrogen. The oxygen reserve requirements are broken down into separate values for the US and RS segments while the nitrogen reserve is maintained on the US segment. For the US, the oxygen reserve is 177 kg (390 lbm).[6] This protects for 6 months WPA use, 10 days OGA downtime, 4 nominal EVAs, 4 contingency EVAs, and 68 kg (150 lbm) of O2 coming from HPGTs. The US O2 reserve supports the multiple purposes as the breakdown suggests, but the underlying goal is to support

ISS needs through a loss of a VV with the assumption that the next VV with resupply will not reach ISS for 6 months. The support is calculated based on nominal usage plus several failure scenarios. The primary failure scenarios that factor into the calculation are the failure of an OGA component and the failure of an external system on ISS that would drive a series of 4 contingency EVAs. The failure of an OGA component is limited to 10 days based on the sparing posture of the components. At least one spare is kept on-orbit for all major components to allow the crew to recover operation through the removal and replacement of that component within 10 days. Ten days was chosen to allow Engineering team time to evaluate the failure and the Operations team time to plan the crew time for the maintenance activity. The support for 4 contingency EVAs is maintained due to a list of potential failures to external systems that require almost immediate response to fix the issue in order to support continued operation of the ISS. The RS O2 reserve is 115 kg (253 lbm) or 45 days of metabolic support. The 45 days is set to account for a loss of the Elektron O2 production and allow time to launch spare or additional O2 to support the crew. The US OGA can support the RS crew, but longer Elektron down times become harder to manage due to USOS water resources. The US segment nitrogen reserve is 104 kg (230 lbm) to allow for the repress of the largest ISS module.[6] There are fire and toxic atmosphere responses that result in the depressurization of a module if the air can not be cleaned up. The N2 reserve allows the depressed module to be repressurized. Additionally, the N2 reserve also provides capability to isolate modules and recover cabin pressure in the remaining volume during a potential "rapid" depress event. The fire/toxic atmosphere and the rapid depress are both scenarios that are protected for, but have not been required to date. There are additional "groundrule" levels that are in place strictly from a planning purposes, but this paper will not go into detail regarding the "groundrule" limits. Table 3 illustrates the planned NORS RTAs needed on near term VV flights to maintain the oxygen and nitrogen systems on board ISS.

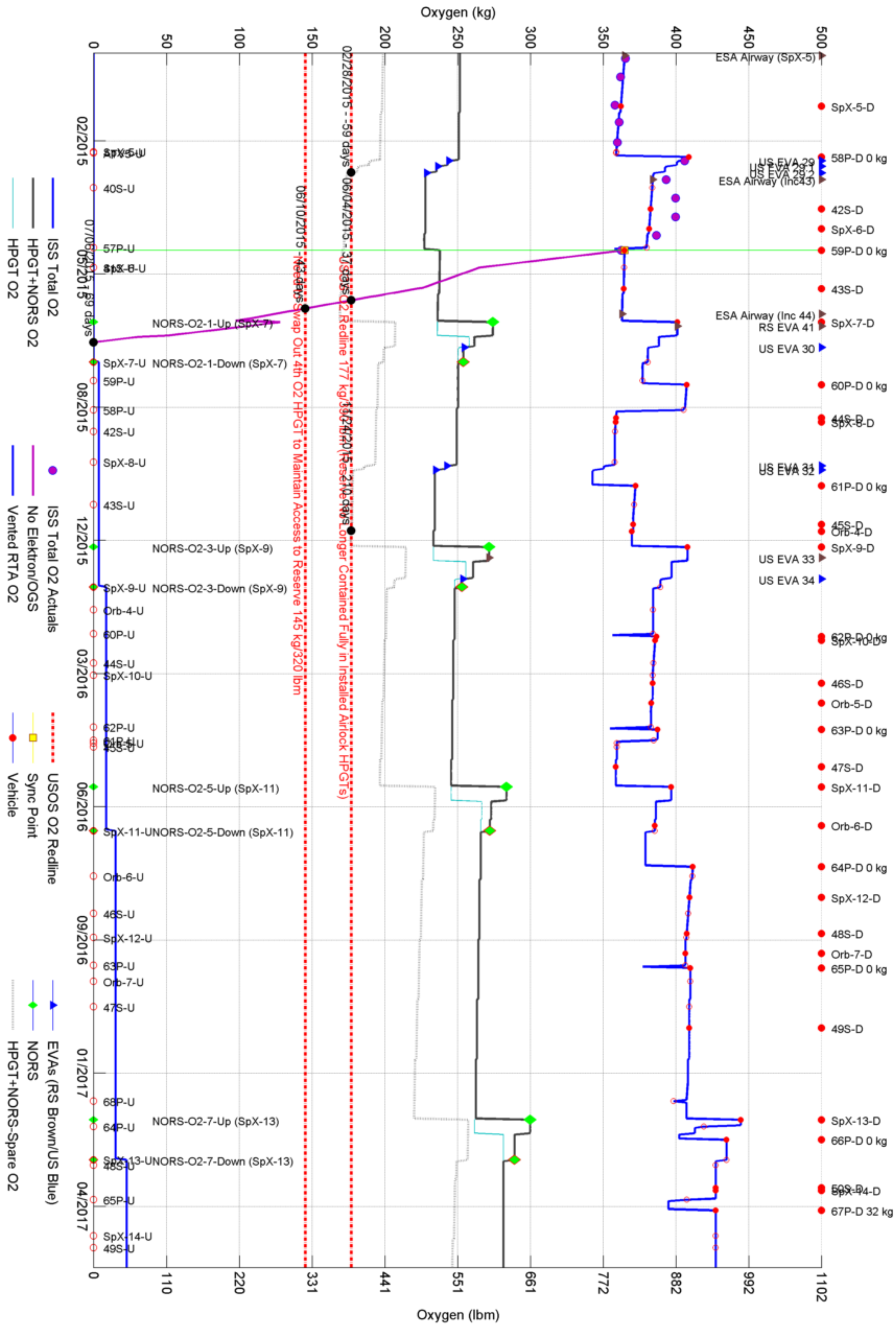

Figure 4 ISS Oxygen Logistics Chart

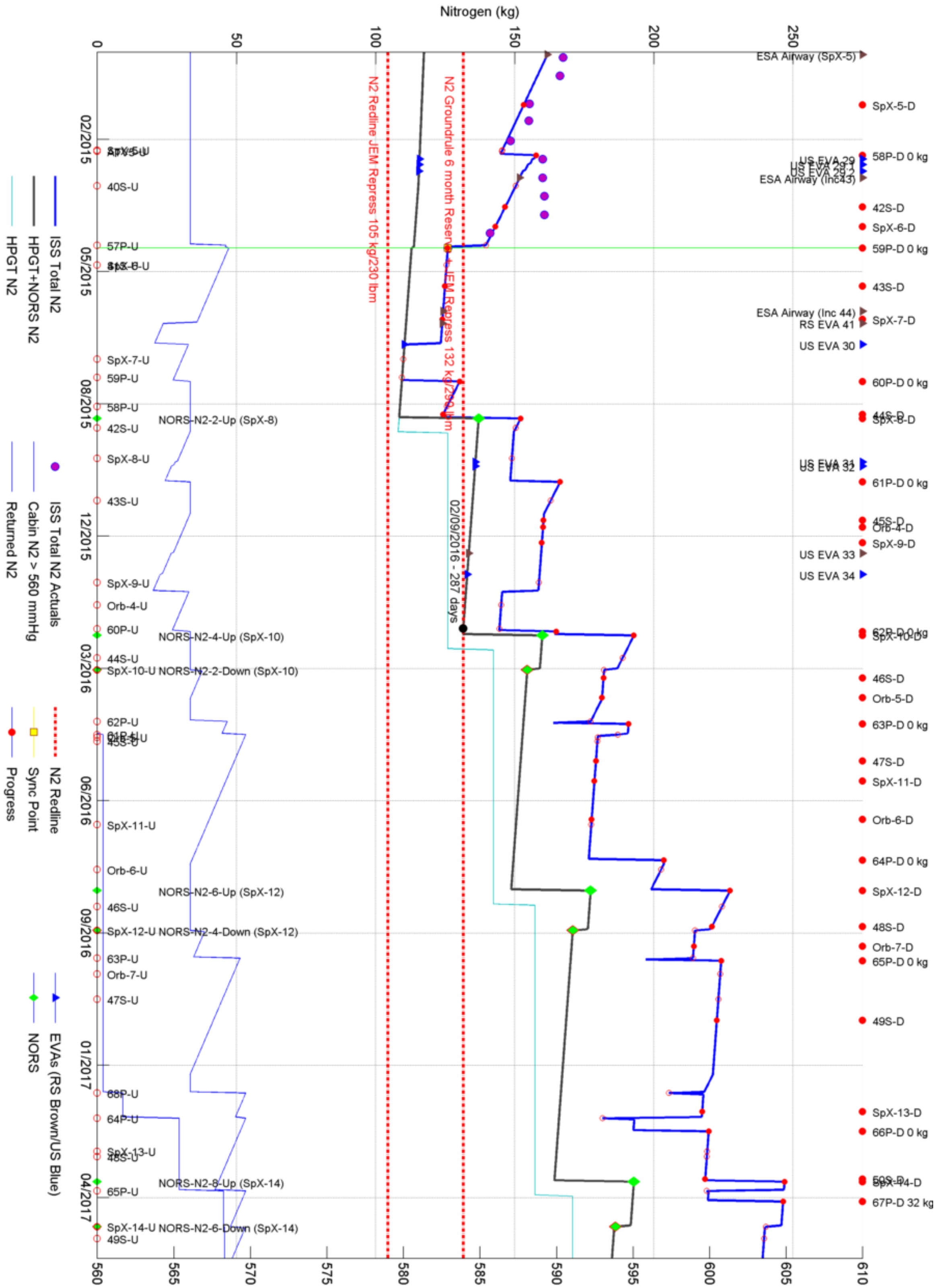

Figure 5 ISS Nitrogen Logistics Chart

Table 3 Near Term Planned NORS RTA Flights

RTA #	Dock Vehicle	Dock Date	Undock Vehicle	Undock Date	N2 (kg)	O2 (kg)
1	SpX-7	06/21/2015	SpX-7	07/21/2015	0.00	38.10
2	SpX-8	09/04/2015	SpX-10	03/15/2016	28.58	0.00
3	SpX-9	12/07/2015	SpX-9	01/06/2016	0.00	38.10
4	SpX-10	02/15/2016	SpX-12	09/25/2016	28.58	0.00
5	SpX-11	06/04/2016	SpX-11	07/07/2016	0.00	38.10
6	SpX-12	08/26/2016	SpX-14	05/07/2017	28.58	0.00
7	SpX-13	02/09/2017	SpX-13	03/11/2017	0.00	38.10
8	SpX-14	04/03/2017	SpX-15	09/07/2017	28.58	0.00

VI. ISS Oxygen/Nitrogen Needs and Usage History

Table 4 and Table 5 show the actual oxygen and nitrogen resupply to ISS since 2008. This includes the last 4 years of Shuttle flights, which provide insight into the transition from Shuttle providing high pressure gases and considerable gas introductions into the cabin. The transition from Shuttle resupply shows up more in the nitrogen data, where the amount of nitrogen (including air) on visiting vehicles is significantly higher than previous years. The visiting vehicle oxygen amounts are more consistent on a yearly basis. The VV oxygen resupply is primarily driven by the need to offset water resupply when there's more capacity than is required for N2 resupply. The VV N2 resupply is driven by RS EVAs and cabin air leakage.

One item of note is that since 2011, there has not been a high pressure resupply of either oxygen or nitrogen. This has led to the O2 HPGTs on the US Airlock to be used only for supporting high pressure operation required for EVAs. Table 6 shows the amount of gas used for EVAs per year. The support of U.S. EVAs has only been possible by topping off of the O2 HPGTs during the final Shuttle flights. The RS EVAs primarily impact the amount of N2 is loaded onto the visiting vehicles.

Table 4 Oxygen Resupply History[4]

Year	Visiting Vehicles (kg/lbm)	Shuttle Cabin Introductions (kg/lbm)	Shuttle High Pressure Transfer (kg/lbm)	Total (kg/lbm)
2008	170/375	78/171	53/117	248/546
2009	168/371	128/281	20/45	296/652
2010	233/514	156/344	31/68	389/858
2011	274/605	127/279	57/127	401/884
2012	223/491	0/0	0/0	223/491
2013	216/475	0/0	0/0	216/475
2014	210/462	0/0	0/0	210/462
2015*	100/220	0/0	0/0	100/220
*Note: Data is through 5/1/2015				

Table 5 Nitrogen Resupply History[4]

Year	Visiting Vehicles (kg/lbm)	Shuttle Cabin Introductions (kg/lbm)	Shuttle High Pressure Transfer (kg/lbm)	Total (kg/lbm)
2008	63/139	237/521	107/237	170/376
2009	57/125	11/24	5/11	62/136
2010	79/175	62/137	28/62	108/237
2011	74/163	49/108	22/49	96/212
2012	119/263	0/0	0/0	119/263
2013	150/330	0/0	0/0	150/330
2014	135/298	0/0	0/0	135/298
2015*	26/57	0/0	0/0	26/57
*Note: Data is through 5/1/2015				

Table 6 EVA Gas Usage History[4]

Year	US EVA O2 Usage (kg/lbm)	RS EVA N2 Usage (kg/lbm)
2008	11/24	-39/-87
2009	0/0	-41/-91
2010	23/51	-51/-113
2011	0/0	-56/-122
2012	19/42	-34/-76
2013	28/62	-89/-197
2014	14/30	-61/-135
2015*	17/36	0/0
*Note: Data is through 5/1/2015		

VII. Conclusion

Over the past 6.5 years, 2081 kg (4589 lbm) of oxygen and 856 kg (1909 lbm) of nitrogen have been supplied to the ISS. The resupplied gas has been critical to the ongoing operation of ISS. The gas has provided metabolic oxygen, EVA support, systems support, atmospheric leakage make-up, and payloads support. Planning of the resupply is continually managed and coordinated with Flight Operations, ISS Program Office, Engineering, and IPs. The type of gas supplied on a given flight is important since the resupply of oxygen impacts the capability to resupply nitrogen.

The Shuttle previously provided a significant means of resupply and was the only means of resupplying high pressure gas. The NORS system was delivered in 2014 and will replace the high pressure gas resupply role that Shuttle previously filled. No NORS tanks have been flown to ISS to date, but multiple tanks are expected to be launched over the next year due to reduced availability of high pressure gas.

VIII. Acknowledgments

The authors wish to acknowledge the support of multiple engineers that have contributed to Atmosphere Control and Supply (ACS) system for ISS. In particular, John Garr and Jason Barbour that are key members of the NASA ETHOS FOD team, Chad Tressler and Aaron Tullos who have worked with the ISS Program to coordinate vehicle gas loading, and Dan Leonard who was instrumental in the original design and assembly of ACS on ISS.

IX. References

[1]Dick, B., "Current Status of the Nitrogen Oxygen Recharge System," AIAA 2011-5226, 41st International Conference on Environmental Systems, Portland, Oregon, 2011.

[2]Generic Groundrules, Requirements, and Constraints Part 1: Strategic and Tactical Planning," Space Station Program 50261-01, Revision E, International Space Station Program, Johnson Space Center, Houston, TX, January 2011.

[3]Leonard, D. J., Rademacher, M., Cook, A. J., Diaz, R., Bullers, B., "Assembly Complete ACS Schematic," Environmental Control and Life Support, The Boeing Company, Internal Release, Houston, TX, 01 March 2011.

[4]NASA FOD ETHOS, "MCC-H Report - ISS Life Support Consumables Status," Internal NASA Website [citied 01 May 2015].

[5]Schaezler, R. N., Cook, A. J., Leonard, D. J., and Ghariani, A., "Trending of Overboard Leakage of ISS Cabin Atmosphere," AIAA 2011-5149, 41st International Conference on Environmental Systems, Portland, Oregon, 2011.

[6]Schulz, E., Tressler, C., "AI 125010, ISS Operational Consumables Reserve," Space Station Program Control Board (SSPCB) Presentation, Johnson Space Center, Houston, TX, 29 April 2014