International Space Station Major Constituent Analyzer On-orbit Performance

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The Major Constituent Analyzer is a mass spectrometer based system that measures the major atmospheric constituents on the International Space Station. A number of limited-life components require periodic change-out, including the ORU 02 analyzer and the ORU 08 Verification Gas Assembly. Improvements to ion pump operation and ion source tuning have improved lifetime performance of the current ORU 02 design. The most recent ORU 02 analyzer assemblies, as well as ORU 08, have operated nominally. For ORU 02, the ion source filaments and ion pump lifetime continue to be key determinants of MCA performance and logistical support. Monitoring several key parameters provides the capacity to monitor ORU health and properly anticipate end of life.

Nomenclature

AR	Atmosphere Revitalization
CH_4	methane
CO_2	carbon dioxide
ECV	electrometer correction value
H_2	hydrogen
H_2O	water
ISS	International Space Station
mA	milliamp
MCA	Major Constituent Analyzer
N_2	nitrogen
O_2	oxygen
ORU	On-orbit Replaceable Unit
S/N	serial number
μA	microamp
VGA	Verification Gas Assembly

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I. Introduction

THE Major Constituent Analyzer (MCA) is a mass-spectrometer-based system designed to monitor nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), methane (CH_4), hydrogen (H_2) and water vapor (H_2O) in the atmosphere of the International Space Station (ISS). It is the primary resource for ensuring that the (O_2) and (CO_2) levels in the ISS atmosphere are maintained at safe levels, and the (N_2) partial pressure reading is used to monitor the ISS for cabin air leakage.

The MCA, shown in Figure 1, is designed as a set of seven On-orbit Replaceable Units (ORUs) that can be serviced or replaced individually in response to periodic maintenance requirements. The modular design approach optimizes logistical support to provide service on limited-life components without having to change out the entire MCA. Of these ORUs, ORU 08 (Verification Gas Assembly) and ORU 02 (Mass Spectrometer Analyzer) are the more commonly replaced subsystems. ORU 02 is the mass spectrometer analyzer that forms the technological core of the MCA. It is comprised of a gas inlet, an ion source, a single-focusing magnetic sector mass spectrometer, six spatially arrayed ion detection electrometers, associated electronics, and a 4 L/sec ion pump. The primary life-limiting items include the ion source filament (of which there are two) and the ion pump. Considerable attention is being paid to determining the factors limiting both the ion pump and ion source lifetimes, as has been described previously[1-5]. To date, the ion pump has been the driving issue for ORU 02 periodic replacement; however, reductions in gas flow and improved operation of the ion pump, implemented under CR10773A, are expected to increase ion pump lifetime. The effect of reduced gas flow on optimal ion source tuning is currently under investigation and will be reported at a later date.

This paper reports the lifetime and performance characteristics of the most recent ORU 02s used in service since our last report in 2012[1], as well as the performance of ORU 08. Review of performance data from these ORU 02s suggests that recent ORU 02 design changes have been successful in increasing ORU 02 life.

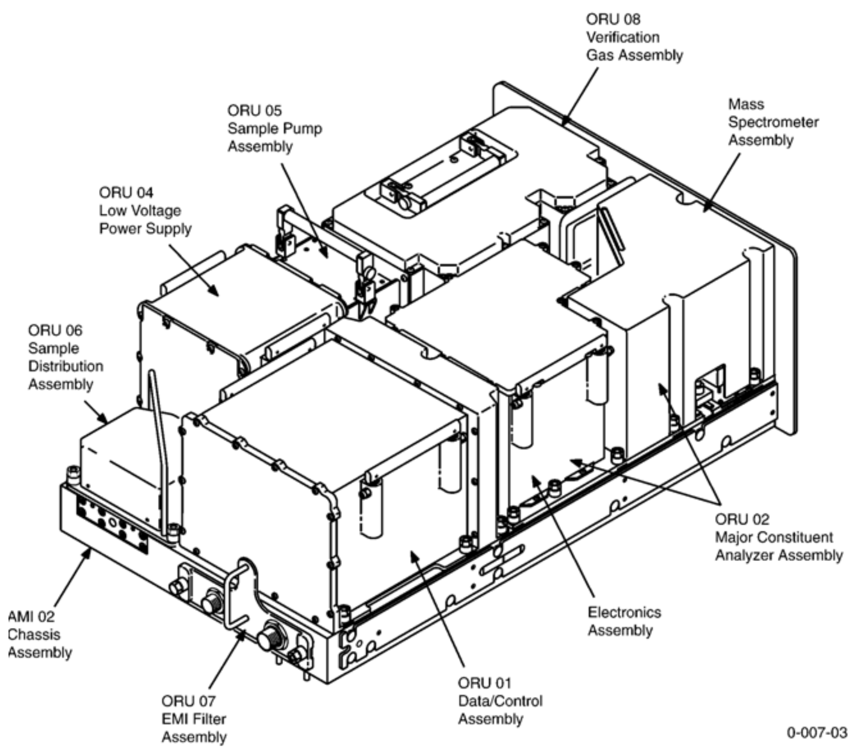

Figure 1: Major Constituent Analyzer

II. On-orbit Activities

A. MCA Transitions On Station

MCA on-orbit activity was last reported at the 2012 ICES Conference1. The MCA in ISS Node 3 is installed in Air Revitalization Rack #2 (AR2) and is operating nominally. ORU 02 F0005 reached end of life in August, 2013 after 19 months service, and was replaced with ORU 02 F0003 which has been operating since September 2013. Sample pump #1 on ORU 05 Q0001 reached end of life in March, 2014. The ORU 05 has redundant pumps, and consequently the Node 3 MCA was restarted successfully using sample pump #2.

In December, 2014, ORU 01 F0002, ORU 02 F0007, and ORU 08 F0003 were installed into the US Lab MCA (AR1) to complete the MCA and provide a second system on orbit for the first time since 2011. ORU 01 F0002 contains the latest firmware, CSCI 4.25, with added capabilities for extending ORU 08 life and improvements to H2O measurement accuracy. At completion of the power-up initialization sequence, the Lab MCA transitioned to FAIL state. Analysis of telemetry indicates that ORU 01 is operating is functioning properly, but that ORU 02 F0007 is not operational. Troubleshooting to further evaluate the installation of ORU 02 F0007 has not been scheduled at this time.

III. ORU 02 Performance Metrics

A. Calibration Stability

ORU 02 analytical stability can be evaluated by tracking the calibration over time. Each ORU 02 is calibrated on the ground to determine its gain characteristics for the detection of each of the major atmospheric constituents. This calibration is based on the responses to gas mixtures of known, very accurately controlled compositions. The resulting calibration values are then programmed into the ORU 02 prior to its protoflight acceptance testing. It is known that the calibration values can change slightly over time for various reasons. Consequently, once on orbit, the ORU 02 calibration is adjusted periodically using a verification gas mixture (a.k.a calibration gas or cal gas). This involves measuring the background offset of each electrometer and determining a gain adjustment factor, the Electrometer Correction Value (ECV). Ideally, if the performance doesn't change, each ECV should stay at or close to a value of 1.0000. Any change in gain value is compensated for by taking the ratio of the expected response (partial pressure of each calibration gas constituent) to the measured response (MCA calculated partial pressures for each constituent) and using that value for the computational correction factor — the ECV. The ECVs are used to adjust the result of MCA partial pressure calculations so that the MCA readout remains calibrated against the known composition of the calibration gas mixture. Experience has shown that the absolute value of ECVs may change with time, but the critical factor is that the ECVs do not change significantly with respect to each other. For trending purposes, the ECVs are "normalized" (i.e., each ECV is divided by the weighted ECV of the three most abundant gases (N_2, O_2 and CO_2)).

B. Ion Pump Current Trending

The ORU 02 ion pump is responsible for maintaining the operational vacuum level of the analyzer, and its degradation over time is historically the primary factor that limits the useful longevity of an ORU 02. Ion pump current is a measure of the gas pumping load and, therefore, analyzer pressure. It is typically 60 to 100 µA at the start of its operating life. In the absence of any parasitic shunt currents that occur as the pump ages, a high ion pump current is indicative of a high pressure internal to the analyzer. The vacuum level of the ORU 02 analyzer must be maintained low enough to prevent the ion source filaments from burning out too quickly, so the MCA is configured to automatically 'safe' the analyzer and protect the filaments when the ion pump current reaches 370 µA. At this point, the MCA generates an error code and goes to FAIL state (i.e., shuts down). The ion pump current is a function of both the gas load and the effects of ion pump wear. Typically, the base ion pump current increases over time and the margin between this current and 370 µA is reduced, eventually leading to ion pump end of life.

C. Filament Current Trending

The ORU 02 ion source contains two filaments which generate the electrons used to create electron ionization (EI) derived ions from the gas molecules. ORU 02 normally uses Filament 1 until it is nearly completely consumed or fails, at which point MCA directs the use of the backup filament, Filament 2. Filament performance is monitored using a filament current sensor upstream in the filament control circuitry, reading the current of the primary of a transformer. The filament current sensor reading (FCS01) normally starts at a reading of 120–150 mA when a filament is new (~135 mA is typical), and gradually decreases over time. The slope of a plot of FCS01 gradually becomes more negative until the value reaches about 100 mA, after which it rapidly becomes steeper and the filament fails shortly thereafter. On-orbit practice is to switch from Filament 1 to Filament 2 when FCS01 decreases to about 108 mA, so that Filament 1 can be retained as a backup to Filament 2 should that filament fail during an essential activity on orbit.

IV. Historical ORU 02 Performance

The historical performances of the ORU 02s that have been used on orbit are listed in Table 1. The performance lifetimes of these ORU 02s has varied from less than a year to nearly 3 years. The primary failure mode has been the result of the ion pump reaching end of life, although several ORU 02s have been replaced earlier to accommodate other on-orbit activity. More recently, two ORU 02s were replaced due to ion source issues discussed briefly below. It is expected that the implementation of modifications to the ion pump operation, as well as adjustments to initial ion source tuning will yield greater durability of future ORU 02s.

Table 1: ORU 02 On-Orbit Usage

ORU 02 Serial No.	Activated	Deactivated	MCA Serial No.	Comments
Q0001	2/12/01	6/23/01	Q0001	Insufficient operating time to accumulate life data.
F0004	6/23/01	4/25/02	F0001	
F0003	9/1/02	9/29/04	F0001	Failed (end of life) with high ion pump current in September 2003. Used in Life Extending Mode until removal in September 2004.
F0002	9/30/04	2/16/06	F0001	Replaced due to increasing frequency of bad zero calibrations due to ion pump noise.
F0001	3/6/06	12/28/08	F0001	Operated 33 months. Removed before end of life to minimize impact to on-orbit operations.
F0004	1/2/09	9/22/09	F0001	Operated 9 months. Had one shutdown due to high ion pump current spike. Was replaced before failure in order to minimize impact to operations.
Q0001	9/25/09	1/23/12	Q0001	Operated 19 months on orbit. High ion pump current. Replaced prior to end of life. Currently serving as on-orbit spare
F0003	9/13/10	10/8/10	F0001	Premature failure of Filament #1. Operated 9/13/10 – 10/8/10 w/ new ORU 01 F0001 and CSCI 4.24.
	5/13/11	6/6/11		Operated 5/13/11–6/6/11 w/ ORU 01 Q0001 and CSCI 4.18. Filament 2 failure.
F0001	7/6/11	7/16/11	F0001	Premature filament failures.
F0005	1/28/12	8/30/13	Q0001	Operated 19 months on orbit. End of life replacement due to high ion pump current spikes.
F0003	9/13/13	--	Q0001	Currently in service. Operating nominally after greater than 600 days.

V. Recent ORU 02 Performance

A. ORU 02 F0005 Performance

ORU 02 F0005 was installed in the Node 3 MCA on January 23, 2012. After a period of pumping down using the ion pump, the MCA was started on January 28, 2012, and the first on-orbit calibration of ORU 02 F0005 was performed on January 31, 2012.

1. Analytical Stability

This ORU 02 performed very well analytically. A plot of normalized ECVs for ORU 02 F0005 for CH_4, CO_2, H_2, N_2, and O_2 is shown in Figure 2. Although the legend lists H_2O, the H_2O values are off scale. Figure 3 includes H_2O ECVs by using an expanded scale.

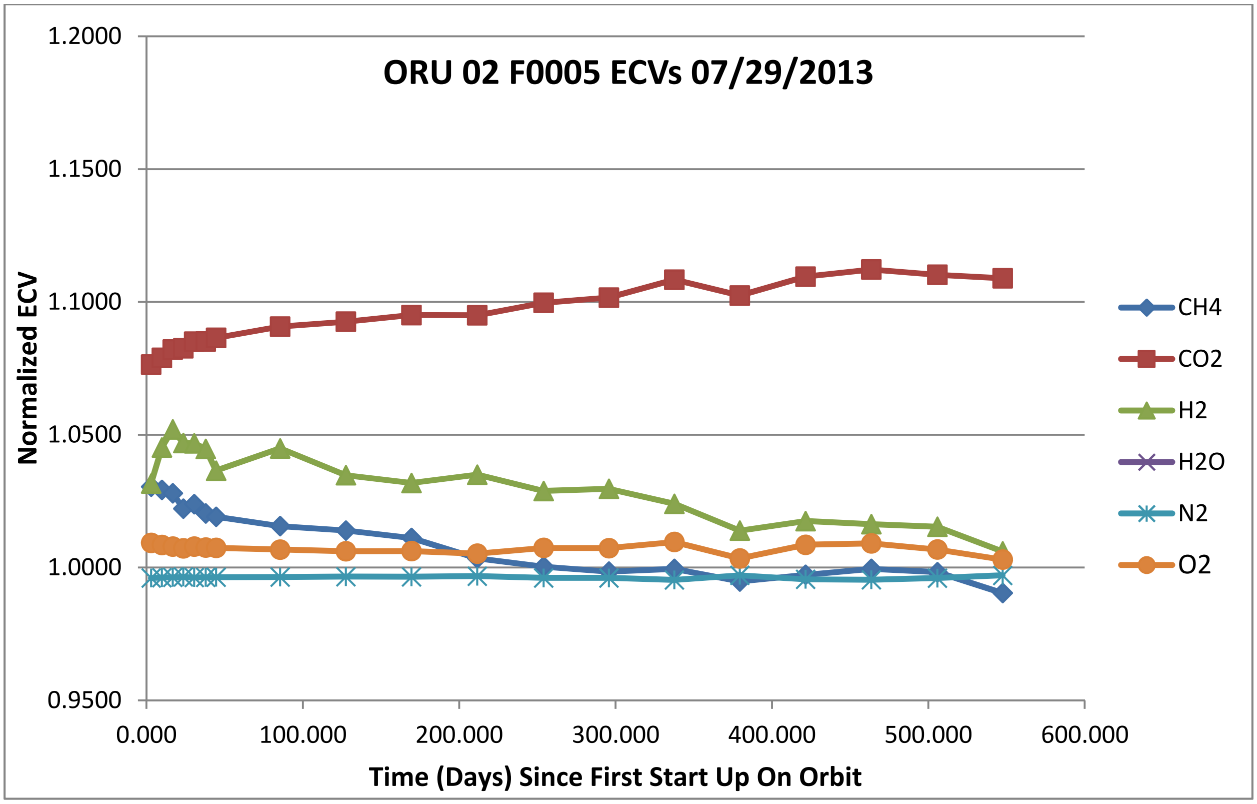

Figure 2: ORU 02 F0005 ECVs

Instrument drift was never a problem. The N_2 and O_2 ECVs were stable. The CO_2 ECV rose about 2.25% in seventy-two weeks, effectively about 0.2% between calibrations. For an ISS ppCO2 of 3 Torr, this would be an error of about 0.006 Torr, well below the +/-0.15 Torr variation expected due to random error. Variations of this magnitude are insignificant to the operation of the Environmental Control and Life Support (ECLS) of the ISS. CH_4 ECVs drifted down of about 2.4% in 72 weeks, and H_2 ECVs drifted down about 4% during this period. Since CH_4 and H_2 have very small partial pressures, errors of this magnitude produce very small resulting errors in the partial pressure measurements.

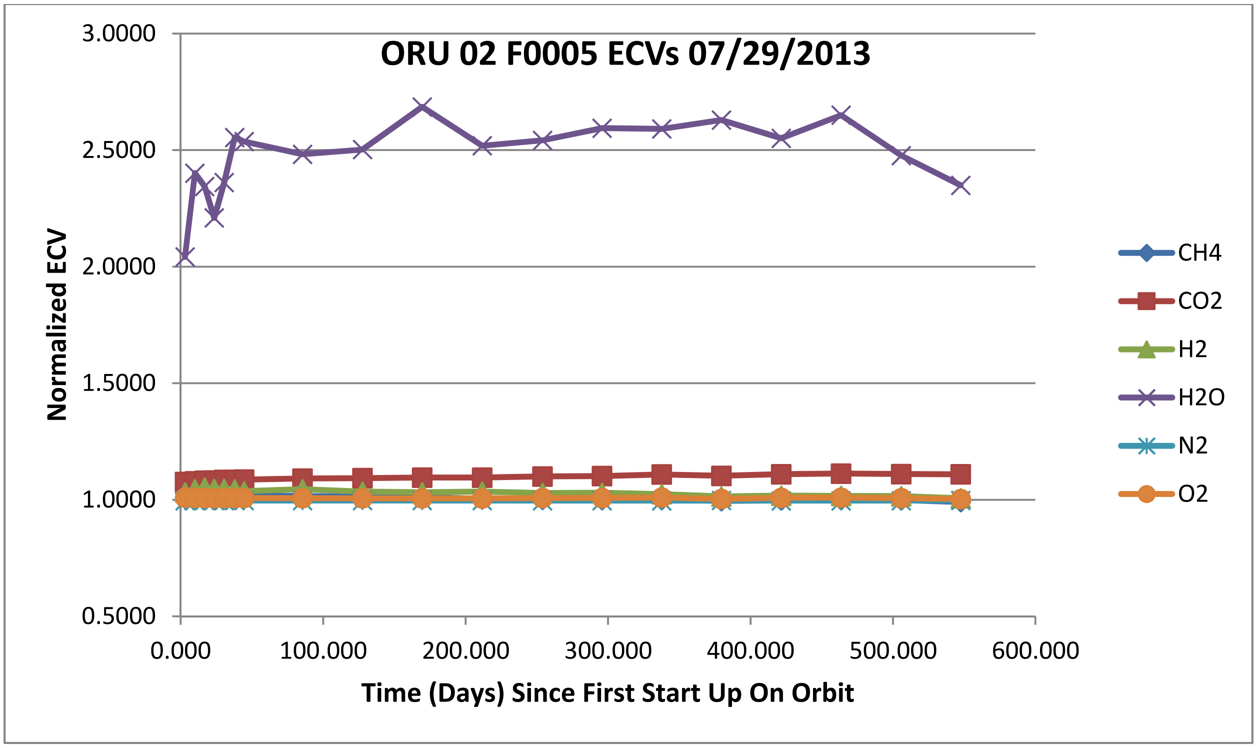

Figure 3: ORU 02 F0005 ECVs Expanded Scale

The water ECV had the largest change between calibrations at about 7%. For a typical ISS water partial pressure of about 11 Torr, an ECV change of this magnitude could lead to an error in water partial pressure of about 0.8 Torr. The calculation of partial pressures normalizes the partial pressures of all gases such that the total equals the total pressure in the compartment being sampled. Because of this, if one gas is overestimated, then other gases are reduced to compensate. In this case, an error of 0.8 Torr in water would cause compensating errors of approximately –0.56 Torr in N_2 partial pressure and –0.24 Torr in O_2 partial pressure, for typical ISS atmosphere composition. Both of these side effects are not considered significant. The compensating errors for CH_4, H_2, and CO_2 are also insignificant.

The ECV data have never shown sufficient drift between calibrations to disturb the analytical performance of any ORU 02 operated on orbit. However, the sensitivity changes due to launch vibration drift over time, and other causes are sufficient to send reported partial pressures out of expected accuracy if on-orbit calibrations are not performed.

2. Filament Performance

ORU 02 F0005 was operated using Filament 1. Filament 1 was nearing the end of its lifetime when the ORU 02 had to be replaced due to ion pump problems. Figure 4 shows the filament current sensor readings obtained during calibrations, with the data for other ORU 02s shown for comparison.

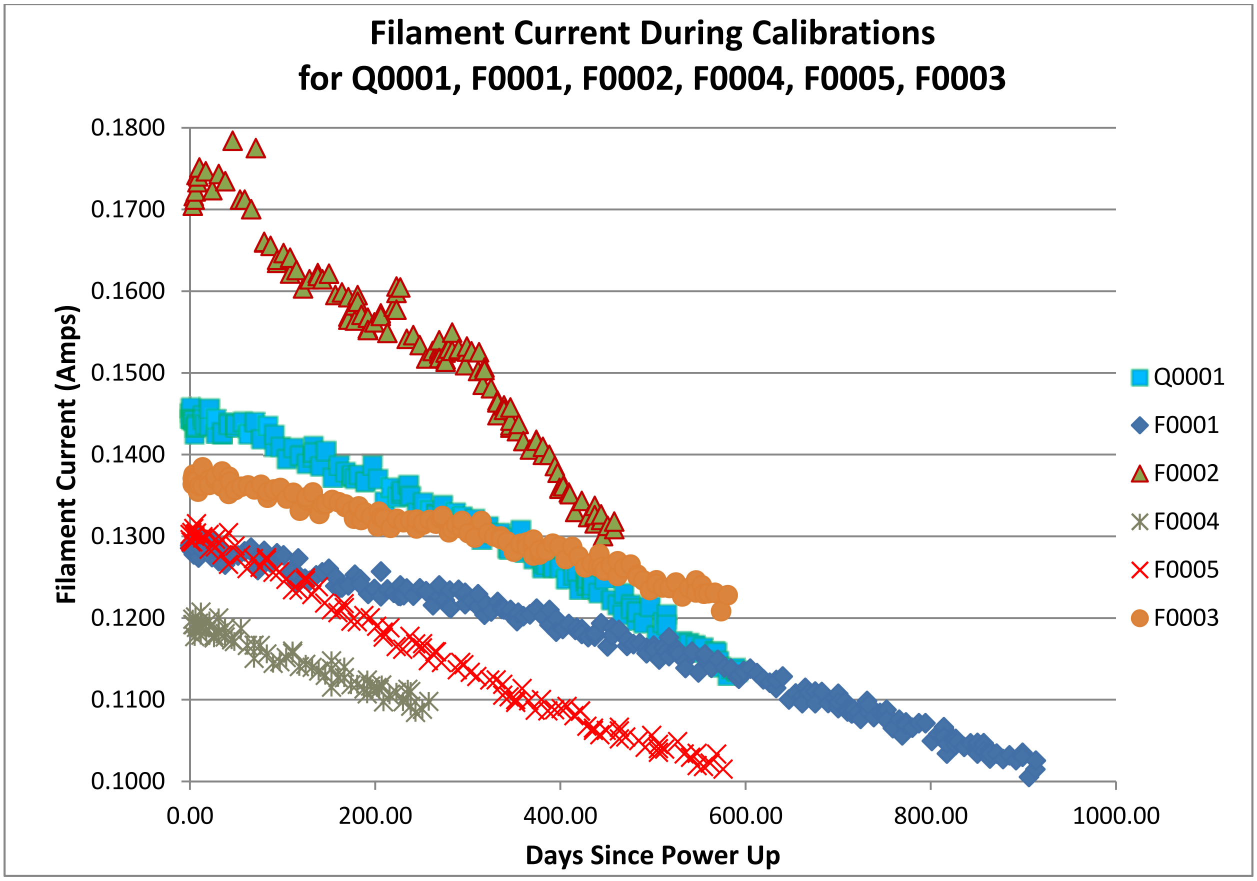

Figure 4: ORU 02 Filament 1 Current Sensor Readings

3. *Ion Pump Performance*

The ORU 02 ion pump is responsible for maintaining the operational vacuum level of the analyzer, and its degradation over time is the primary factor that limits the useful longevity of an ORU 02. The ion pump high voltage of F0005 was lowered about 17 percent compared to previous ion pumps. Ground testing indicated the lower ion pump voltage would extend the ion pump life. F0005 was the first ORU 02 on orbit with this reduced high voltage, and there was keen interest in the effect of the voltage reduction on ion pump life.

The ion pump current of F0005 was more stable than for previous ORU 02s. Figure 5 shows the ion pump current measurements for F0005 during 550 days of operation. The graph shows 10-minute averaged data. Telemetry actually provides an updated value every 10 seconds, so each data point in the graph is the average of 60 readings. The main trace is the ion pump current during normal operation when the pressure at the inlet leak of the mass spectrometer is approximately 336 Torr (6.5 psia). Occasional drop downs by half occur when the MCA is placed in Standby state or another state with no sample valve open. At such times, the pressure at the inlet leak drops to about 170 Torr. The values also occasionally drop when the MCA is taken out of operation, such as when maintenance is being performed. These are rare events, since the MCA generally operates continuously.

The ion pump current of F0005 showed a gradual rise of about 13 µA per year. The ion pump current when the inlet valve is closed (i.e., no gas load) is only about 2 µA. Near the end of operation of F0005, the ion pump current was composed of about 70 µA due to pumping and 20 µA of parasitic shunt current.

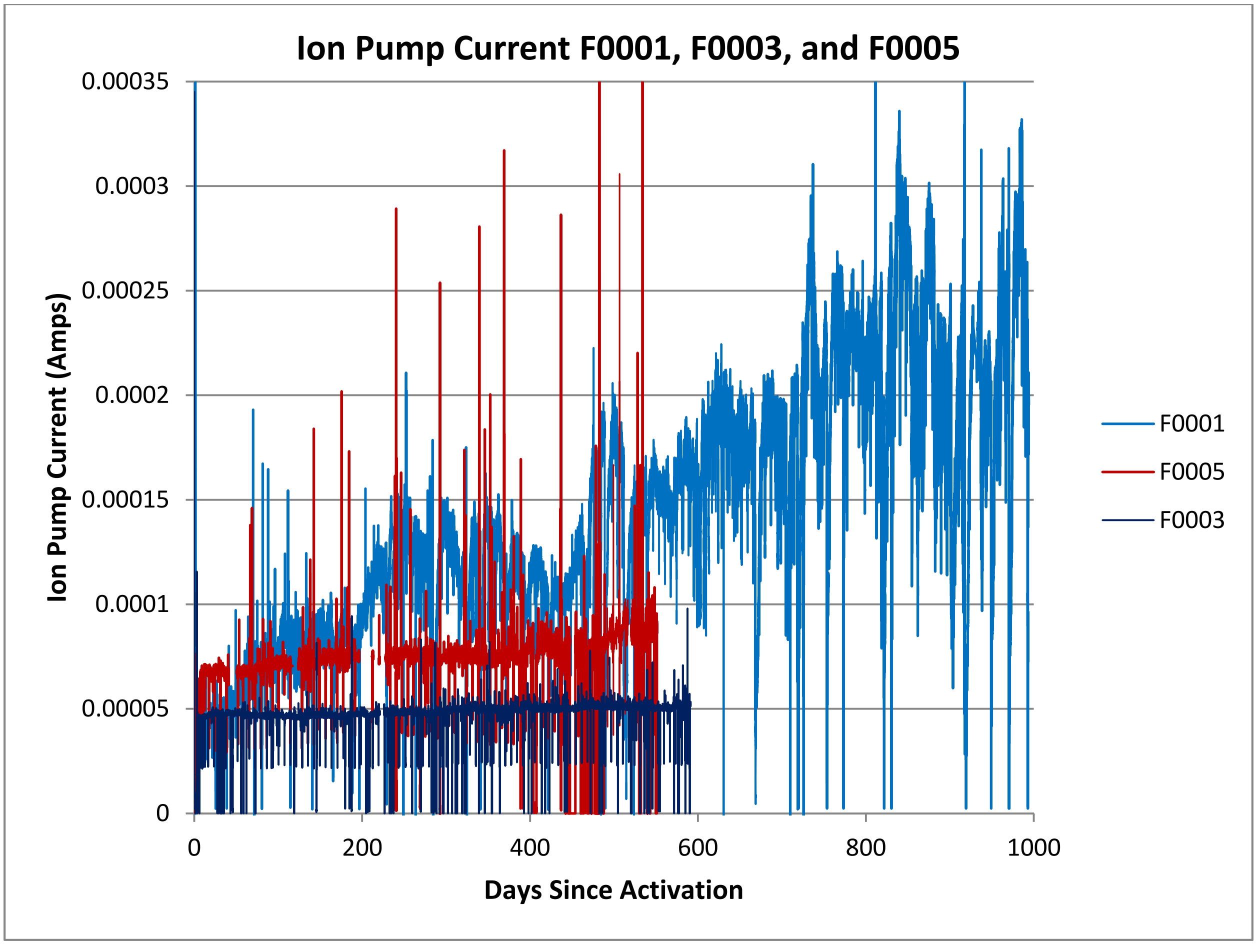

Figure 5: Ion Pump Current for ORU 02 F0001, F0005, and F0003

In contrast to the performance of F0005, the ion pump current trend for ORU 02 F0001 showed an increase of ion pump current of about 70 µA per year. A rise of ion pump current has been typical of the performance of ion pumps in the past, with rates varying from 80 µA per year to several hundred µA per year. The much lower rate of increase of the ion pump current of ORU 02 F0005 is attributed to the lower ion pump high voltage.

B. ORU 02 F0003

ORU 02 F0003 was installed in the Node 3 MCA on September 13, 2013. ORU 02 was pumped down and the ion pump was activated. After three days, on September 16 at approximately 7 pm, F0003 was fully activated. The first on-orbit calibration of ORU 02 F0003 was performed on September 19, 2013. To this point, the performance of F0003 has been the best of all ORU 02s flown. It still must maintain performance until about April of 2016 to outlast F0001's record for operational duration.

1. Analytical Stability

This ORU 02 performed very well analytically. A plot of normalized ECVs for ORU 02 F0003 for CH_4, CO_2, H_2, N_2, and O_2 is shown in Figure 6. Although the legend lists H_2O, the H_2O values are off scale. Figure 7 includes H_2O ECVs by using an expanded scale.

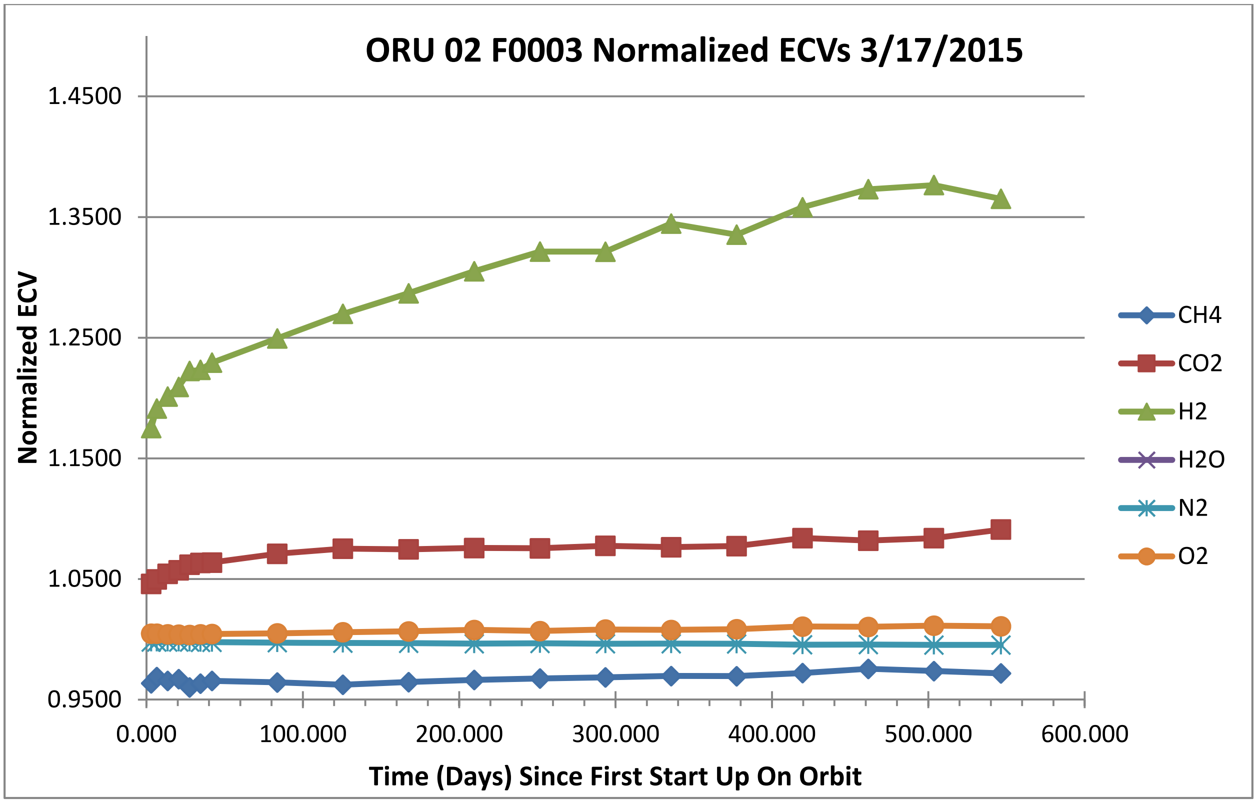

Figure 6: ORU 02 F0003 ECVs

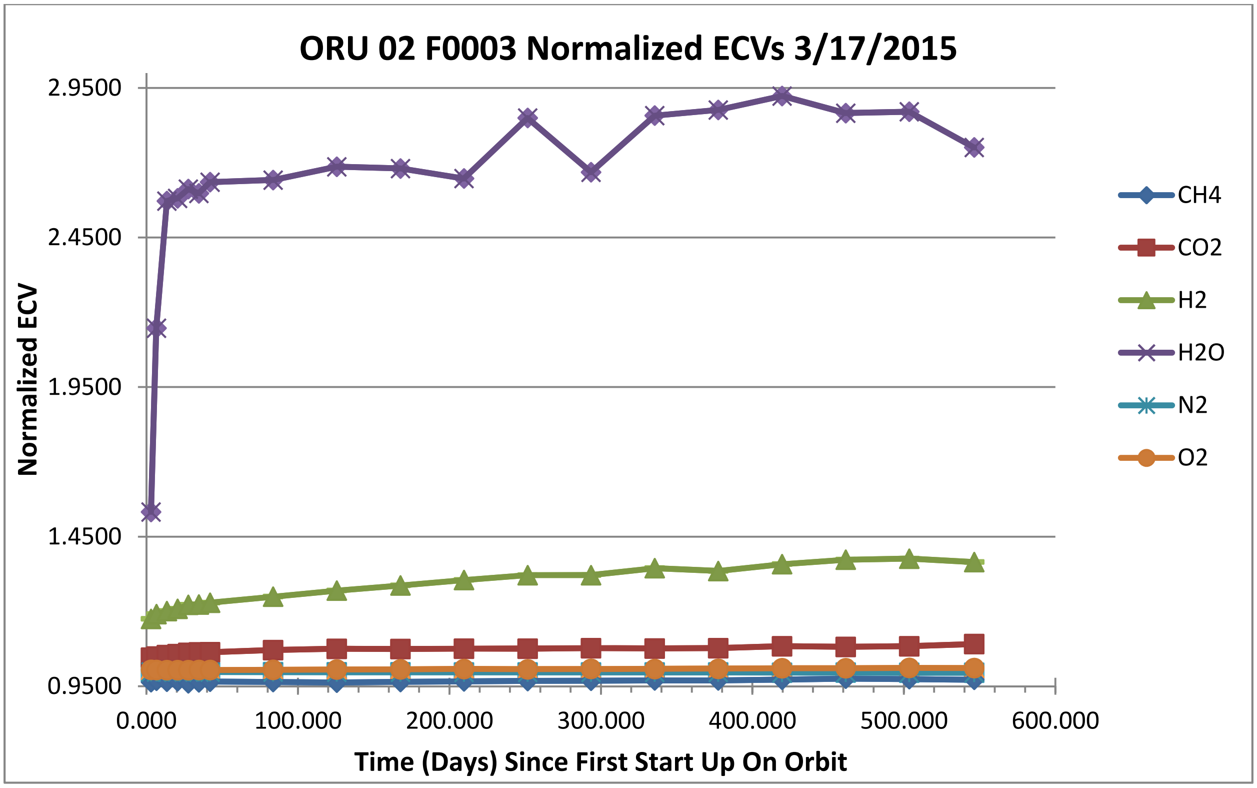

Figure 7: ORU 02 F0003 ECVs Expanded Scale

Instrument drift has not been a problem. The CH_4, CO_2, N_2, and O_2 ECVs are stable. The H_2 ECV has risen about 11% in the seventy-two weeks since initial instrument stabilization, almost 1% during each 6-week interval between ECV calibrations. Since H_2 has a very small partial pressure, errors of this magnitude produce very small resulting errors in the partial pressure measurements.

The water ECV had the largest change between calibrations at about 8%. For a typical ISS water partial pressure of about 11 Torr, an ECV change of this magnitude could lead to an error in water partial pressure of about 0.9 Torr. The calculation of partial pressures normalizes the partial pressures of all gases such that the total equals the total pressure in the compartment being sampled. Because of this, if one gas is overestimated, then other gases are reduced to compensate. In this case, an error of 0.9 Torr in water would cause compensating errors of approximately –0.63 Torr in N_2 partial pressure and –0.27 Torr in O_2 partial pressure, for typical ISS atmosphere composition. Both of these side effects are not considered significant. The compensating errors for CH_4, H_2, and CO_2 are also insignificant.

2. *Filament Performance*

ORU 02 F0003 has operated using Filament 1. Figure 4 shows the filament current sensor readings obtained during calibrations, with the data for other ORU 02s shown for comparison. The filament current curve extrapolates to a total lifetime of about 1200 days. If this lifetime is actually achieved, the filament will hold the record for on-orbit operation.

3. *Ion Pump Performance*

ORU 02 F0003 is the second ORU 02 on orbit with the reduced high voltage. The ion pump current of F0003 has thus far been more stable than for any previous ORU 02. Figure 5 shows the ion pump current measurements for F0003 during 590 days of operation. The graph shows 10-minute averaged data. The ion pump current of F0003 has shown a gradual rise of about 6 µA per year. The ion pump current when the inlet valve is closed (i.e., no gas load) is only about 2 µA. The ion pump current is only about two thirds of the current value of ORU 02 F0005, probably due to lower gas conductance of the inlet leak. Given the low operating current, this ion pump is expected to last longer than previous ion pumps.

VI. ORU 08 Performance

A. ORU 08 Q0001 Performance

ORU 08 Q0001 is the source of verification gas (cal gas) during Full Calibration procedures for the Node 3 MCA. Some cal gas is also consumed during restarts of the MCA. While ORU 02 F0003 has been operated, the cal gas has been consumed at an average rate of about 0.55 psi per day. The tank pressure reading is about 440 psia, and the ORU can supply gas until its pressure drops below 70 psia. At the current rate of consumption, this ORU 08 can supply the Node 3 MCA with cal gas for about another 670 days, i.e., until about January of 2017.

VII. US Lab MCA

The US Lab MCA has been inactive but was reactivated in December, 2014. To make it operable, a new ORU 08, ORU 01 F0002, and ORU 02 F0007 were installed. ORU 01 F0002 has new firmware, version 4.25, which had not previously been operated on orbit. The MCA powered up and established 1553B communication with the ISS Control and Data Handling system. The new firmware seems to be operating correctly.

At completion of power up initialization, the MCA transitioned to FAIL state. Analysis of telemetry indicates that the new ORU 02 F0007 is not operational. The symptoms are consistent with a damaged wiring harness connector. The Lab MCA is currently off, waiting for crew time to troubleshoot the ORU 02 problem. Repair recommendations will depend on what is found during the trouble shooting.

VIII. Conclusion

The MCA in Node 3 continues to supply the ISS with reliable, stable partial pressure measurements for the major constituents of the ISS atmosphere. Barring unexpected problems, ORU 02 F0003 in the Node 3 MCA will probably supply measurements for at least another year. Since the US Lab MCA is not currently operational, there is not currently a redundant MCA.

References

[1]Gardner, B. D., Erwin, P. M., Thoresen, S. M., Granahan, J. and Matty, C., “International Space Station Major Constituent Analyzer On-orbit Performance,” *42nd International Conference on Environmental Systems*, San Diego, CA, 2012.

[2]Gardner, B. D., Erwin, P. M., Thoresen, S. M., Granahan, J. and Matty, C., “International Space Station Major Constituent Analyzer On-orbit Performance,” *40th International Conference on Environmental Systems*, Barcelona, Spain, 2010.

[3]Gardner, B. D., Erwin, P. M., Lee, W. T., Tissandier, A. M. and Thoresen, S. M., “Improving the Measurement Accuracy of Water Partial Pressure Using the Major Constituent Analyzer,” *39th International Conference on Environmental Systems*, Savannah, GA 2009.

[4]Thoresen, S. M., Steiner, G. and Granahan, J., “International Space Station (ISS) Major Constituent Analyzer (MCA) On-orbit Performance,” *38th International Conference on Environmental Systems*, San Francisco, CA 2008.

[5]Steiner, G., Thoresen, S. M., Reysa, R. and Granahan, J., “International Space Station (ISS) Major Constituent Analyzer (MCA) On-orbit Performance,” *36th International Conference on Environmental Systems*, Norfolk, VA 2006.