47th International Conference on Environmental Systems
10-14 July 2016, Vienna, Austria ICES-2016-362

International Space Station Major Constituent Analyzer On-orbit Performance

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The Major Constituent Analyzer (MCA) 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. The most recent ORU 02 and ORU 08 assemblies are operating nominally. For ORU 02, the ion source filaments and ion pump lifetime continue to be key determinants of MCA performance. Additionally, testing is underway to evaluate the capacity of the MCA to analyze ammonia. Finally, plans are being made to bring the second MCA on ISS to an operational configuration.

Nomenclature

AR	Atmosphere Revitalization
CH_4	methane
CO_2	carbon dioxide
CSCI	Computer Software Configuration Item
ECV	electrometer correction value
H_2	hydrogen
H_2O	water
ISS	International Space Station
mA	milliamp
MCA	Major Constituent Analyzer
N_2	nitrogen
NH_3	ammonia
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[1-6]. To date, the ion pump has been the driving issue for ORU 02 periodic replacement; however, operation of the ion pump at a lower voltage, implemented under CR10773A, is expected to increase ion pump lifetime.

This paper reports the lifetime history and recent performance characteristics of the ORU 02 used in service over this past year, as well as the performance of ORU 08. Review of performance data from recent ORU 02s suggests that ORU 02 design changes have been successful in increasing ORU 02 life. Also described is the possibility of adapting the MCA to detect ammonia (NH_3); and finally, the current status of the second MCA, currently located in the ISS U.S. Lab, is summarized.

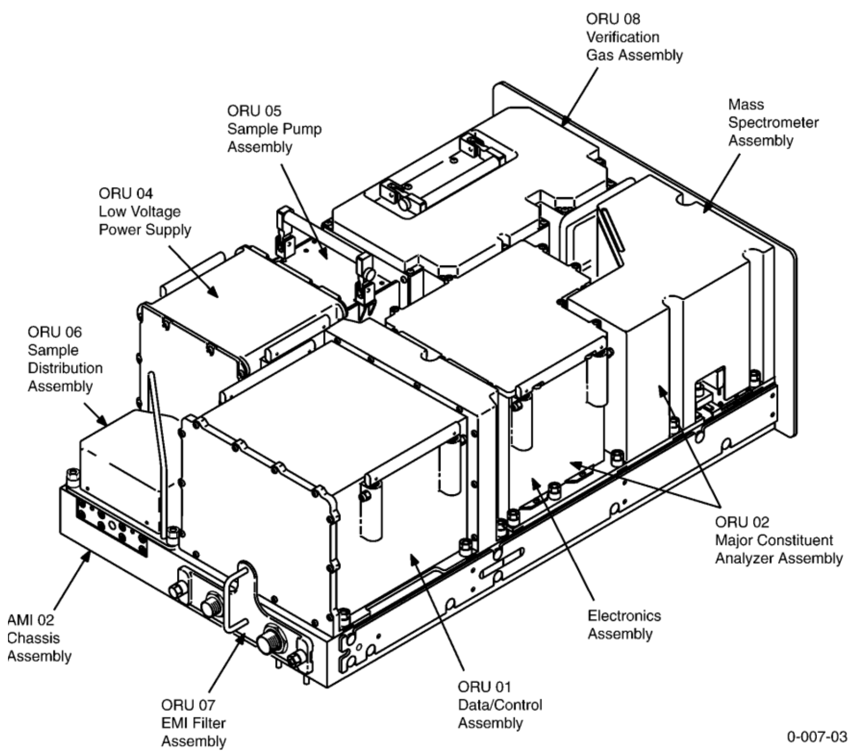

Figure 1: Major Constituent Analyzer

II. On-orbit Activities

A. MCA Transitions On Station

MCA on-orbit activity was last reported at the 2015 ICES Conference[1]. 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 H_2O 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 functioning properly, but that ORU 02 F0007 is not operational. Troubleshooting to further evaluate the installation of ORU 02 F0007 has not been scheduled by the ISS Program 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

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

V. Recent ORU 02 Performance

D. ORU 02 F0003

ORU 02 F0003 was installed in the Node 3 MCA on September 13, 2013. It was immediately pumped down and the ion pump activated. After three days, on September 16, ORU 02 F0003 was fully activated. The first on-orbit calibration of ORU 02 F0003 was performed on September 19, 2013. It was approved for improved accuracy operation 6 weeks later. Since that time, the performance of ORU 02 F0003 has been outstanding. No anomalous issues have been reported, and performance characteristics support the conclusion of this being the best of all ORU 02s flown thus far. If it maintains performance until April of 2016, it will outlast ORU 02 F0001's record for operational duration.

1. Analytical Stability

This ORU 02 is performing very well analytically. A plot of normalized ECVs 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 using an expanded scale.

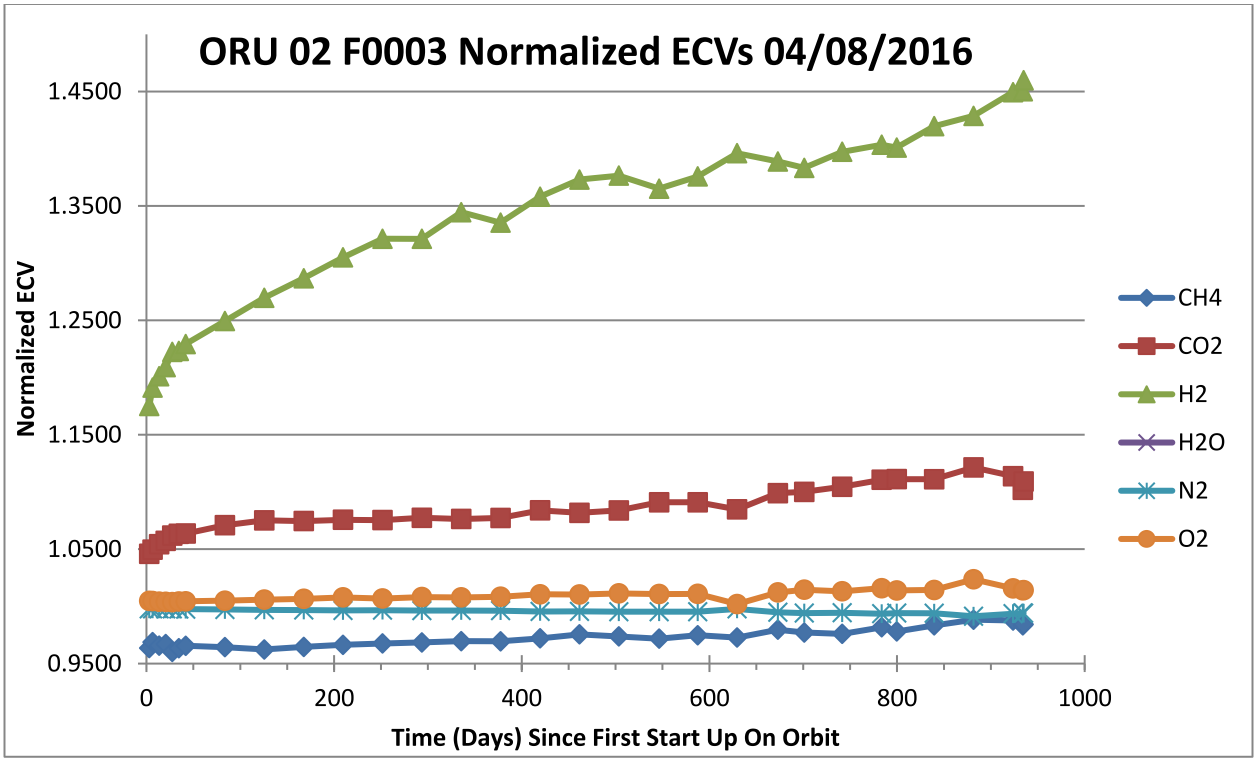

Figure 2: ORU 02 F0003 On-orbit ECVs

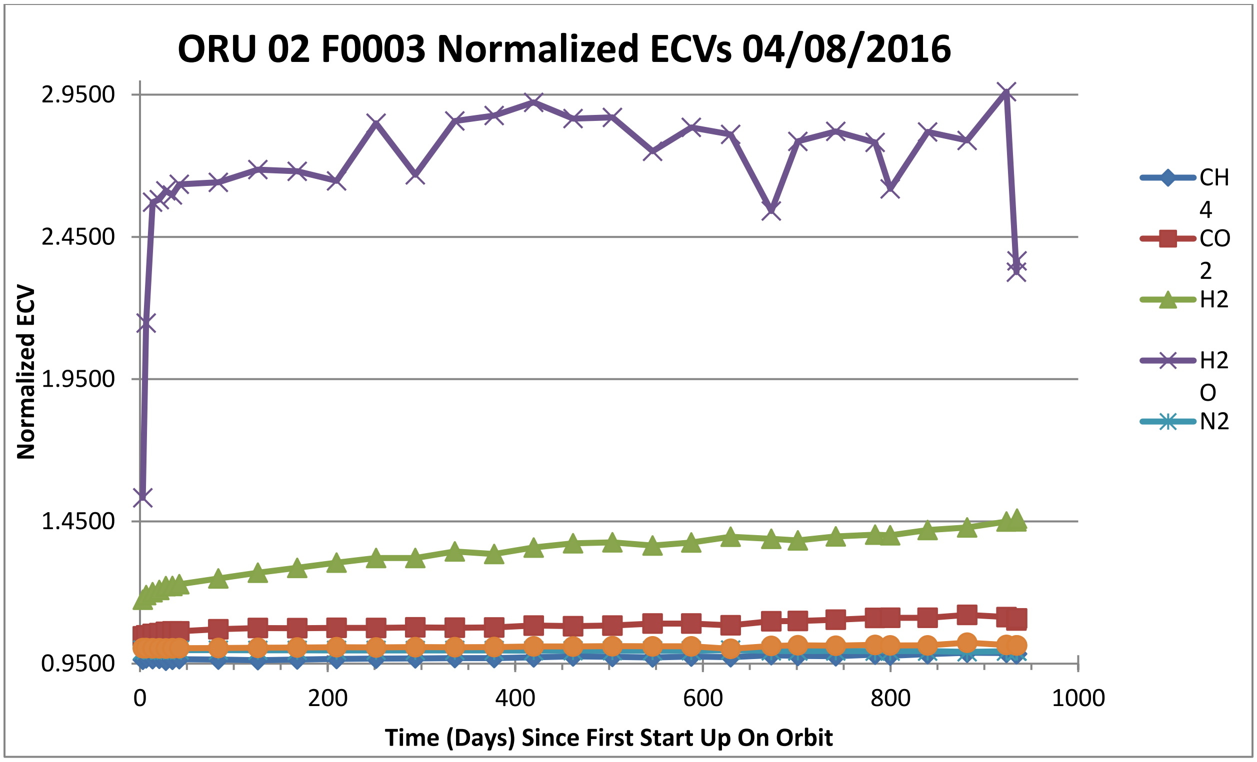

Figure 3: ORU 02 F0003 On-orbit ECVs Expanded Scale

The CH_4, CO_2, N_2, and O_2 ECVs are stable and instrument drift has consequently not been a problem. The H_2 ECV has risen approximately 24% in the 133 weeks since initial instrument stabilization, which is approximately 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 approximately 8%. For a typical ISS water partial pressure of approximately 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. Note that Figure 3 shows a shift of the H2O ECV from about 2.95 to 2.36 at the latest measurement. This is due to the installation of new MCA firmware 4.25, which has an updated methodology for water calculation and calculates a different H2O ECV.

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 F0003 has been operating 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 approximately 1200 days. This corresponds to the time at which the filament reaches a minimum 0.10 Amp current limit previously established. Filament 1 holds the record for on-orbit operation.

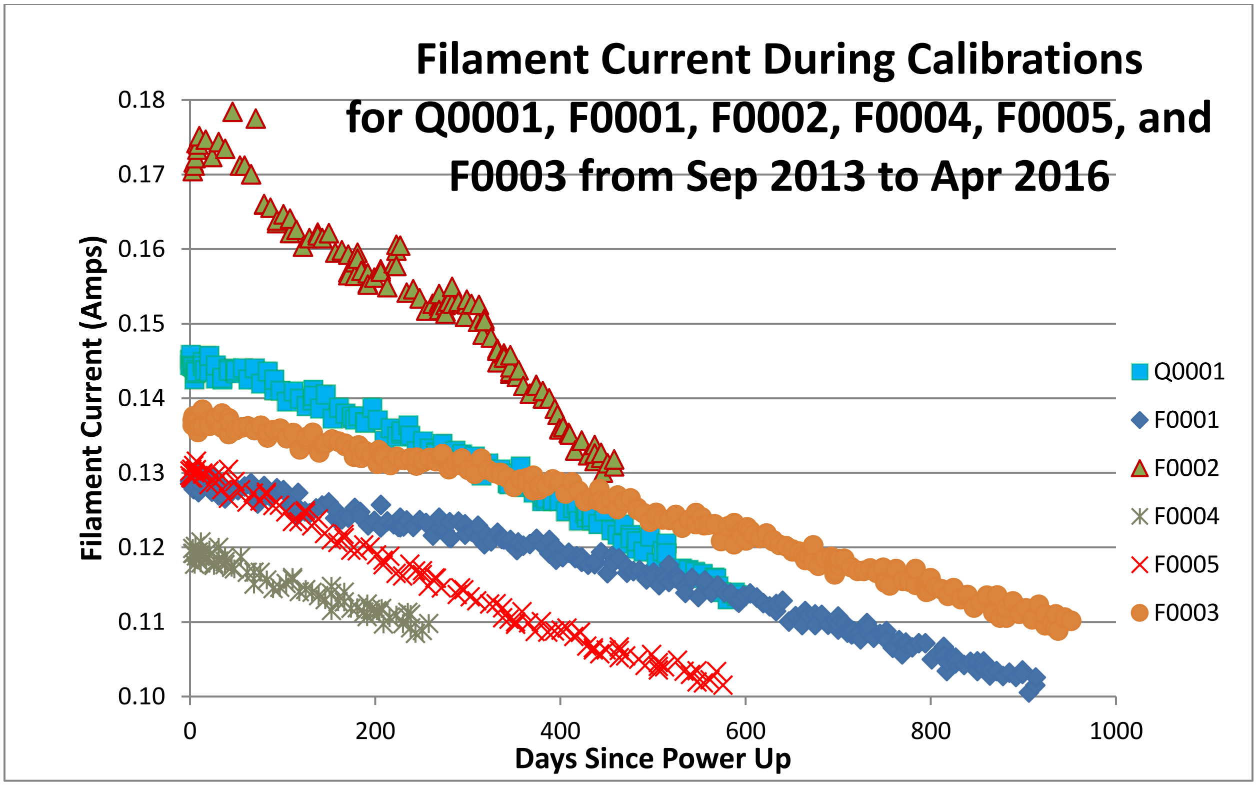

Figure 4: ORU 02 Filament 1 Current Sensor Readings

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 895 days of operation. The graph shows 10-minute averaged data. The ion pump current of F0003 has shown a gradual rise of about 2 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.

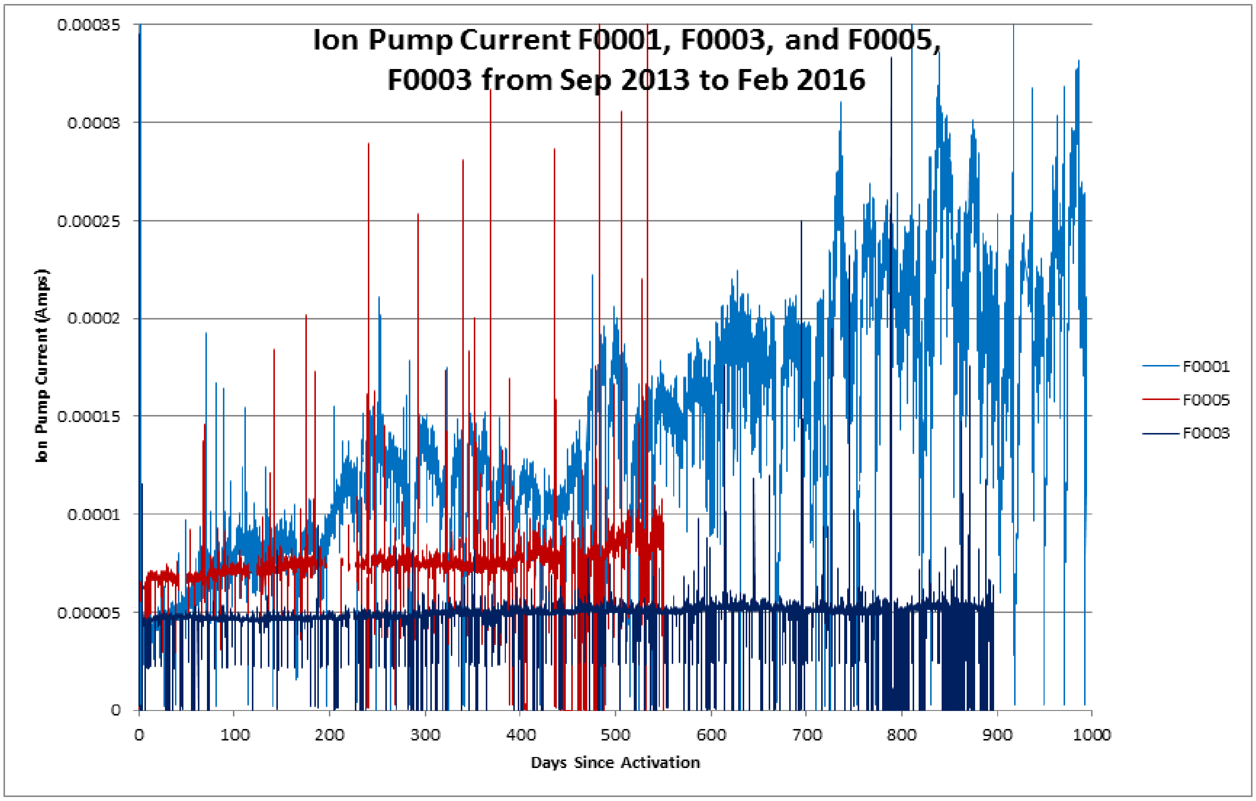

Figure 5: Ion Pump Current for ORU 02 F0001, F0005, and F0003

VI. ORU 08 Performance

A. ORU 08 Q0001 Performance

ORU 08 Q0001 is the source of verification gas during Full Calibration procedures for the Node 3 MCA. A small amount of verification gas is also consumed during restarts of the MCA. While ORU 02 F0003 has been operated, the verification gas has been consumed at an average rate of about 0.56 psi per day. The tank pressure reading is approximately 257 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 verification gas until about January of 2017.

VII. Using MCA to monitor Ammonia

Recent events on ISS have motivated an examination of the extent to which MCA could be retasked to detect NH_3. The external cooling system for ISS uses NH_3 as the thermal transport medium, and even a minor leak within ISS would pose a significant health hazard to the crew. Consequently, there is a desire to provide continuous monitoring at detection levels below the permissible exposure limit (PEL).

Testing of the MCA for NH_3 sensing capability is currently underway, and initial data acquired using the engineering Integration and Test Unit (ITU) has demonstrated that NH_3 monitoring with MCA is feasible. Additional testing to determine limits of detection will be performed in the near future.

VIII. US Lab MCA

The US Lab MCA has been inactive but was reactivated in December, 2014. The reactivation activity included installation of a new ORU 08, ORU 01 F0002, and ORU 02 F0007. The 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.

During the reactivation activity, 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 issue. Repair recommendations will depend on what is found during the trouble shooting.

IX. Node 3 MCA ORU 01 R&R

ORU 01 is the subassembly that includes the processor, memory, 1553B communication interface, and most of the support electronics of the MCA. This includes electronics to measure the pressure transducers PT02 (ORU 06 manifold pressure), PT04 (verification gas supply line pressure), and PT05 (verification gas tank pressure). On April 4, 2016, these transducers began giving erroneous values, causing the Built-In Test (BIT) firmware to shut down the MCA. Analysis of telemetry data indicated that an Operational Amplifier (OpAmp) on a circuit card in ORU 01 Q0001 failed. At that time, ORU 01 Q0001 had been operating nearly continuously for fifteen years.

On April 7, 2016, ORU 01 Q0001 was replaced by ORU 01 F0001. After power up, the pressure transducer readings returned to expected values, confirming that the problem was in the ORU 01 electronics and not in the pressure transducers themselves. The new ORU 01 has a newer version of firmware, version 4.25, than the replaced ORU 01, which had version 4.18. The performance of the MCA with this new firmware will be reported at a later date.

ORU 01 Q0001 is slated for down manifest and will be returned to UTAS Pomona for investigation of the failure and service. Even without failure of the OpAmp, the program expected this ORU 01 to need to be returned for service soon, since the non-volatile memory that holds the firmware is rated by the manufacturer for ten years, and it had already been approximately 15 years since the firmware was programmed into the EEPROM.

X. 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 operational, there is not currently a redundant MCA. However, once the troubleshooting of ORU 02 F0007 is complete, the Lab MCA is expected to be made fully operational.

References

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